Performance Measures for Intelligent Systems

From
Theory to Experiment

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PerMIS?03, Performance Metrics for Intelligent Systems, 16-18 Sep 2003, Gaithersburg, MD

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Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

History

PerMIS'00 -- definition of intelligence

PerMIS'01 -- metrics and measures of intelligence

PerMIS'02 -- methods to perform measurements

PerMIS'03 -- large experiments, data collection

FY03 Major Experiments

ARL/GDRS - Demo III TRL-6 experiments

NIST - TRL-6 terrain characterization data collection

DARPA - PerceptOR off-road perception experiments

DARPA - MARS Urban Search and Rescue Arenas

Boeing/FCS - Integrated Combat Demonstration

FY03 Data Collection

Terrain Characterization Data

- **High resolution LADAR for geometry**
- **High performance INS/GPS for position**
- **Instrumented trailer for soil mechanics**

Woods and fields, desert terrain, snow, urban

Roads and traffic

NIST campus

TRL-6 Experiments

Nov'02 - Fort Indiantown Gap – Woods and fields

Dec'02 - Tooele Army Depot – Desert sagebrush

Jan'03 – Fort Indiantown Gap – Woods, trails, snow

Apr'03 - Fort Indiantown Gap – Urban environment

Total of 550 km distance traversed
Over 90% autonomous operation (distance, time)
Quantitative measures of operator interventions

TRL-6 Experiments +
FCS Integrated Combat Demo

PerceptOR
Off-Road Perception

Team Raptor

Team Blitz

PerceptOR Goals

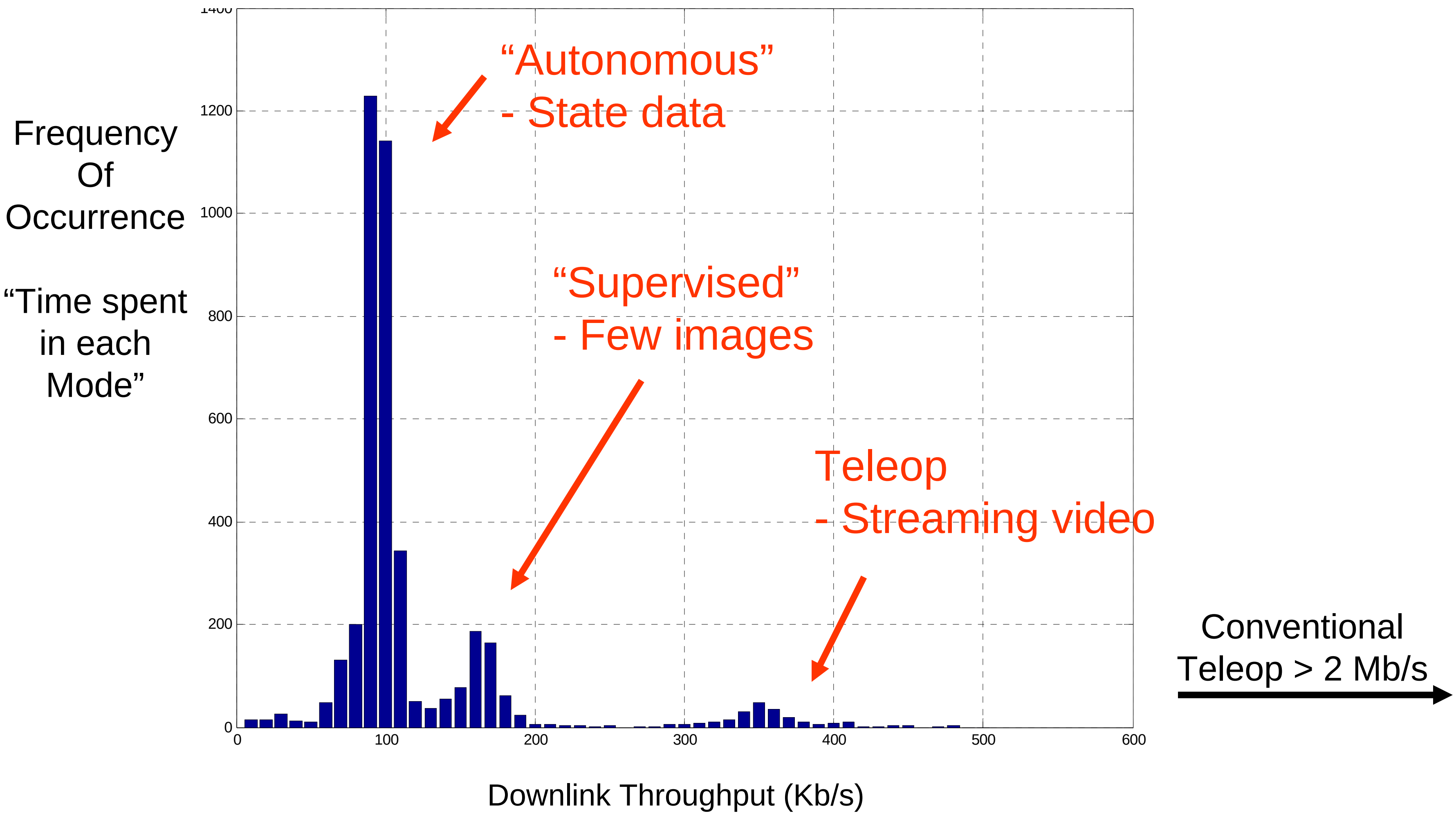
- Apply perception systems to dense obstacle environments
- Minimal sensor development (off the shelf)
- Develop algorithms while testing in the field

PerceptOR Status

- **Phase II concluded – DEC 02**
  - **Four field tests in 2002**

- **Phase III initiated**
  - **Focus on Technical Thrusts**
  - **Two Performers**
    - **Team Blitz – CMU Prime**
    - **Team Raptor – SAIC Prime**
  - **(2) Contract tests at their facility in 1st half of 2003**
  - **(2) Government tests in 2nd half of CY 2003**

PerceptOR
Ph II Communications



DARPA MARS
Urban Search & Rescue Testbed

- **3 Robotic USAR Competitions**
  - -- RoboCup 2003, Rome, Italy
  - -- IJCAI 2003, Acapulco, Mexico
  - -- U. S. RoboCup Rescue Open 2003, CMU
- **Scored competitions**
- **Analysis of system performance**

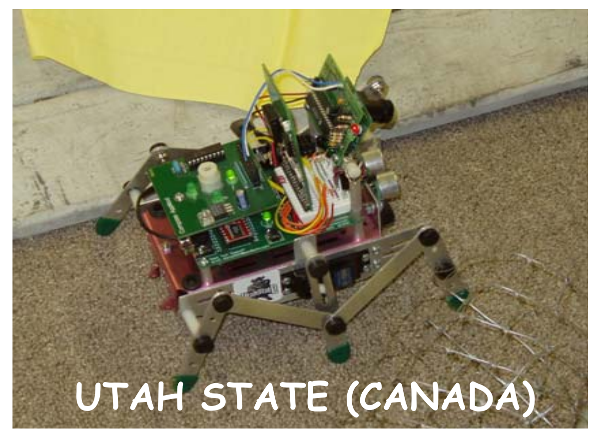
IJCAI/AAAI ARENAS
(MEXICO, 2003)

YELLOW ARENA

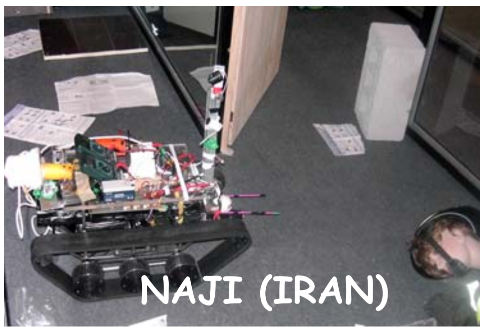
ORANGE ARENA

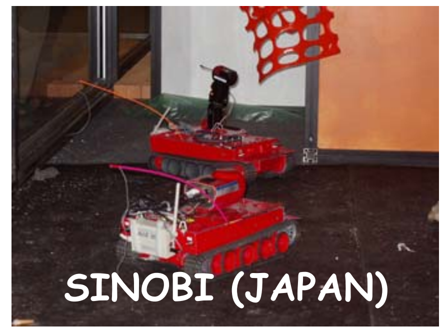
RED ARENA

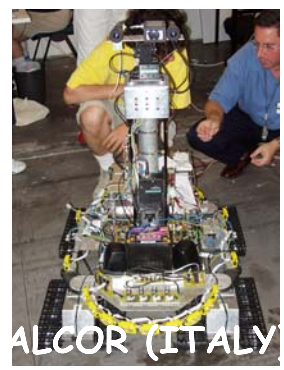
IJCAI/AAAI ROBOTS
(MEXICO, 2003)



ROBOCUP ROBOTS
(ITALY, 2003)





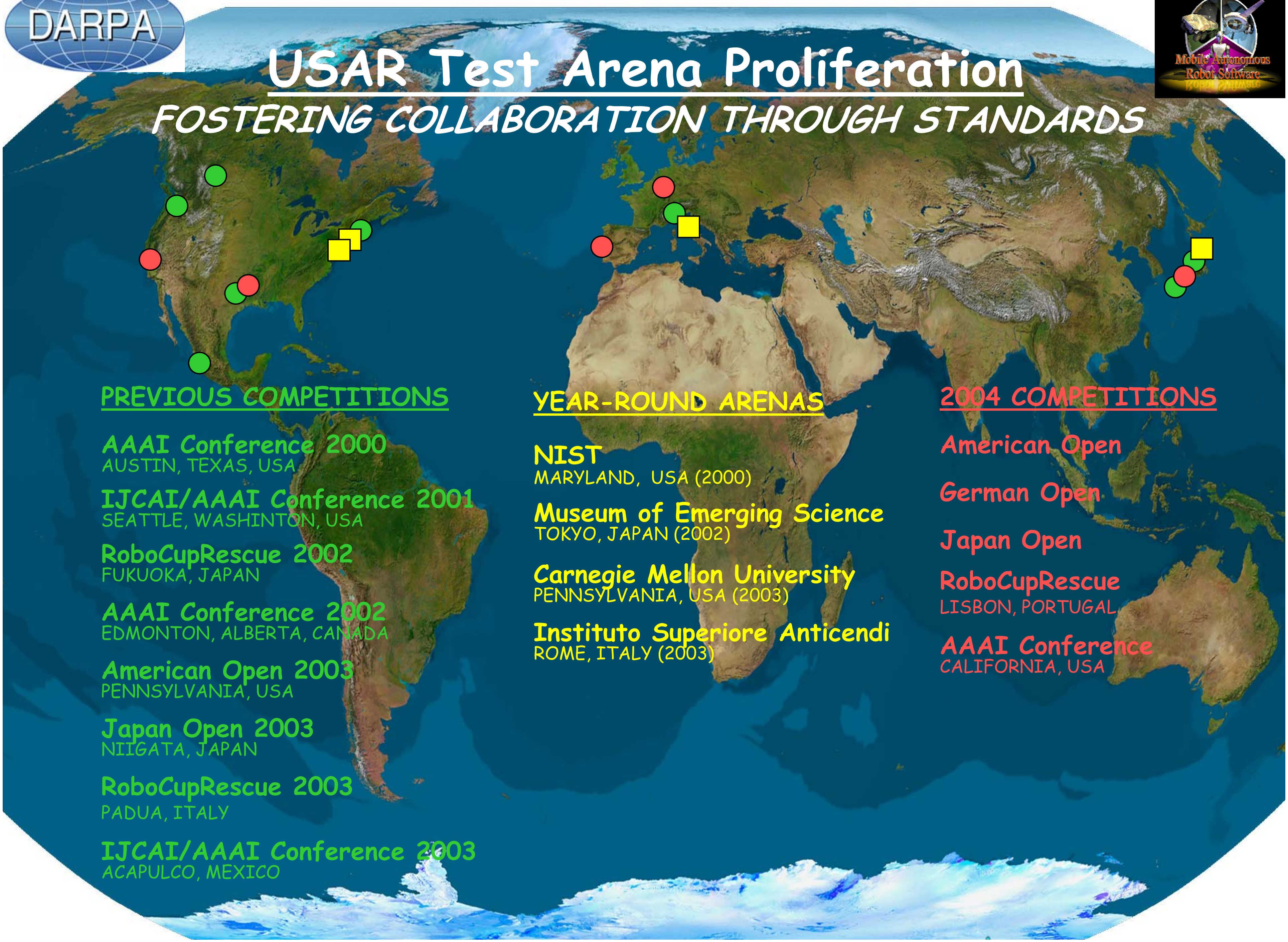


USAR ROBOT PERFORMANCE METRIC

$$\text{ARENA WEIGHTING}\left(\frac{\overbrace{\text{MAP QUALITY} + \text{VICTIM LOCATION} + \text{VICTIM SITUATION} + \text{VICTIM STATE} + \text{VICTIM TAG}}^{\text{50 POINTS POSSIBLE PER VICTIM FOUND}} \overbrace{- \text{ARENA BUMPING} - \text{VICTIM BUMPING}}^{\text{PENALTIES PER EVENT}}}{\left[1 + \text{NUMBER OF OPERATORS}\right]^2}\right)$$

USAR Test Arena Proliferation

FOSTERING COLLABORATION THROUGH STANDARDS



PREVIOUS COMPETITIONS

AAAI Conference 2000
AUSTIN, TEXAS, USA

IJCAI/AAAI Conference 2001
SEATTLE, WASHINTON, USA

RoboCupRescue 2002
FUKUOKA, JAPAN

AAAI Conference 2002
EDMONTON, ALBERTA, CANADA

American Open 2003
PENNSYLVANIA, USA

Japan Open 2003
NIIGATA, JAPAN

RoboCupRescue 2003
PADUA, ITALY

IJCAI/AAAI Conference 2003
ACAPULCO, MEXICO

YEAR-ROUND ARENAS

NIST
MARYLAND, USA (2000)

Museum of Emerging Science
TOKYO, JAPAN (2002)

Carnegie Mellon University
PENNSYLVANIA, USA (2003)

Instituto Superiore Anticendi
ROME, ITALY (2003)

2004 COMPETITIONS

American Open

German Open

Japan Open

RoboCupRescue
LISBON, PORTUGAL

AAAI Conference
CALIFORNIA, USA

HIGH RESOLUTION LADAR FOR TERRAIN CHARACTERIZATION

NIST HMMWV

at Tooele Army Depot

Dec. 9-13, 2002

Mike Shneier, Tsai Hong, Tommy Chang,

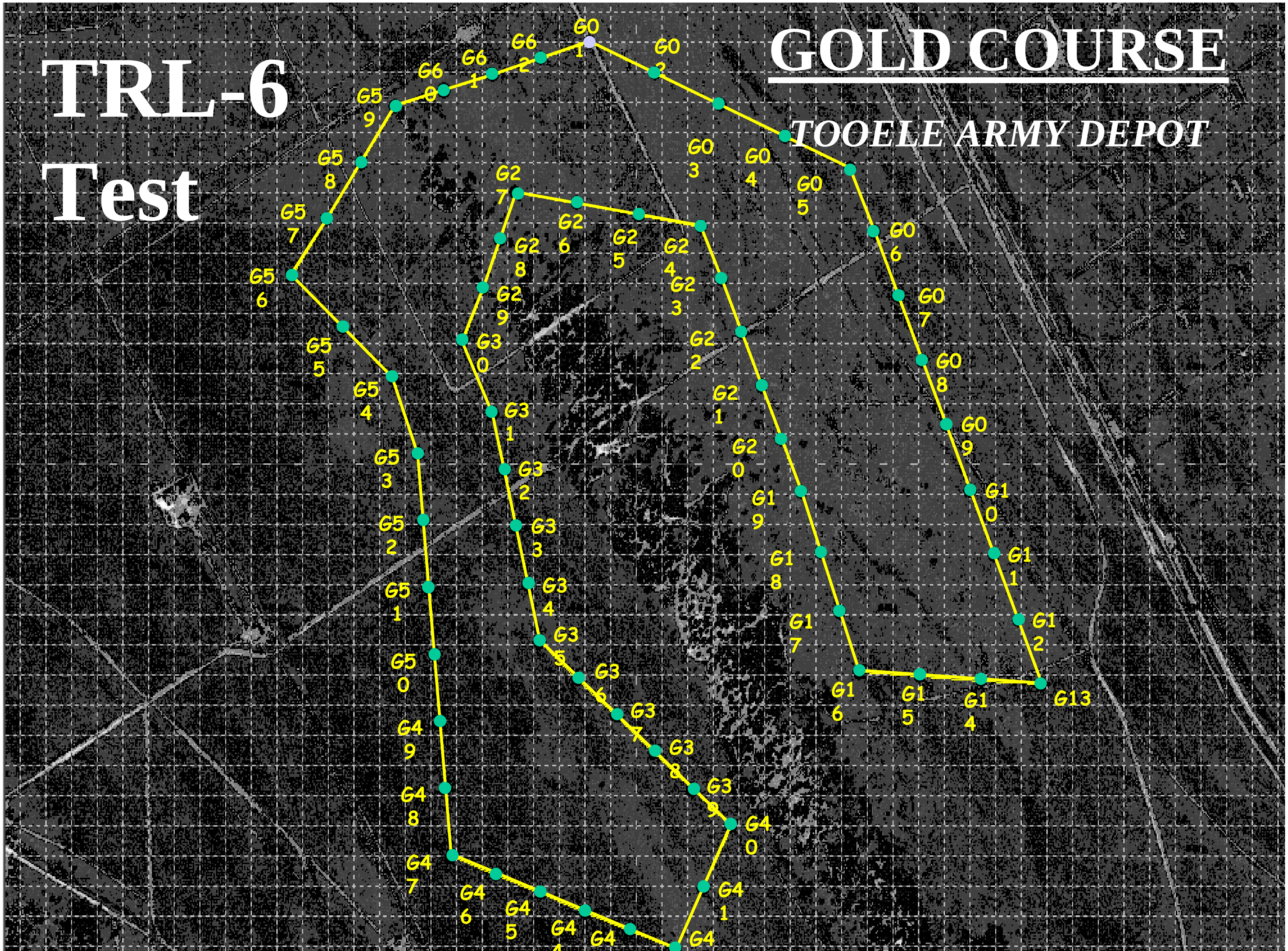
Harry Scott, Steve Legowik, Gerry Cheok, Chuck Giauque

Intelligent Systems Division

National Institute of Standards and Technology

Terrain Characterization Testbed

Terrain Characterization Testbed at Tooele Army Depot

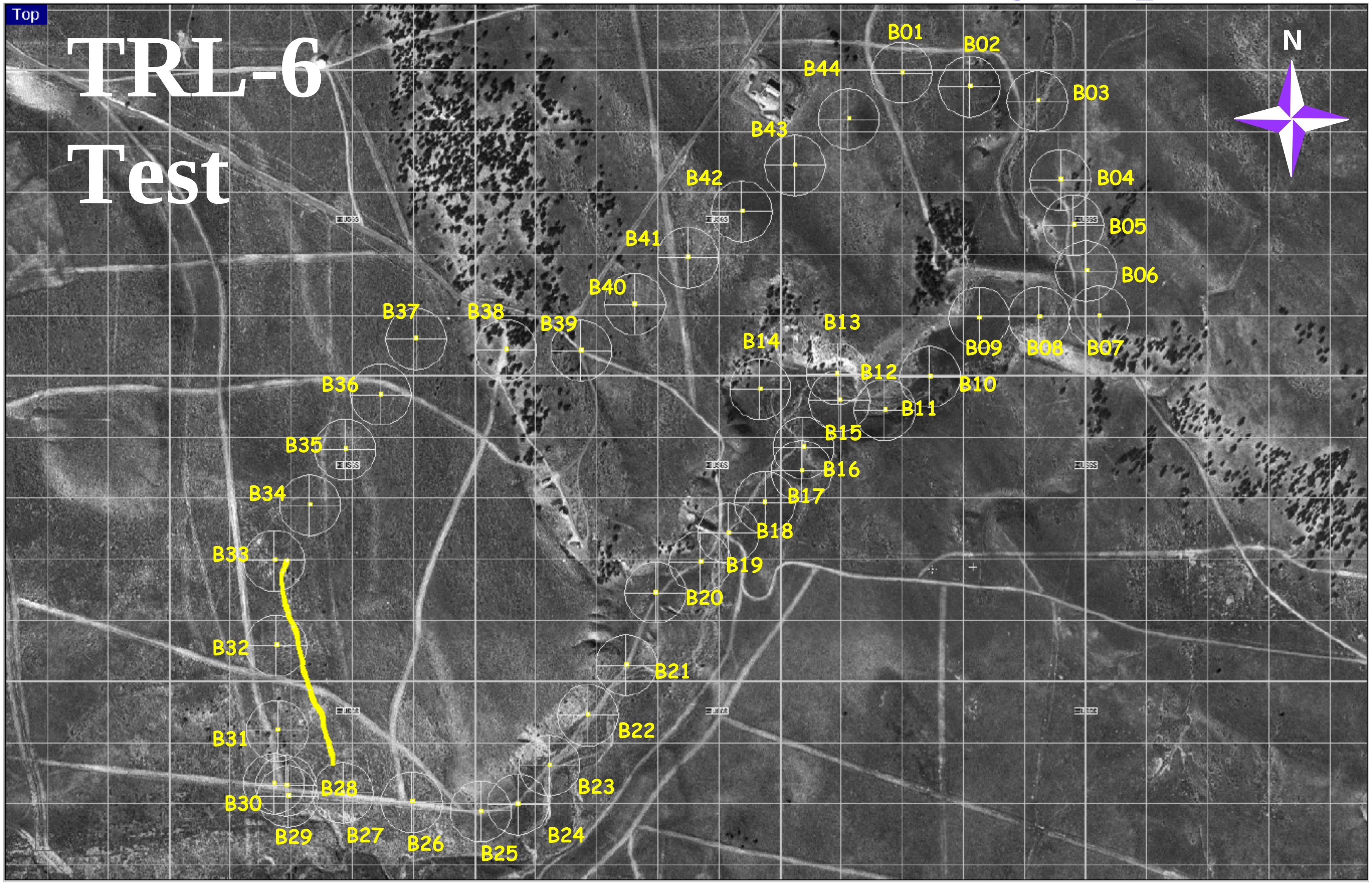


GENERAL DYNAMICS Robotic Systems

ROBOTIC RESEARCH

NIST

Black Course: Tooele Army Depot

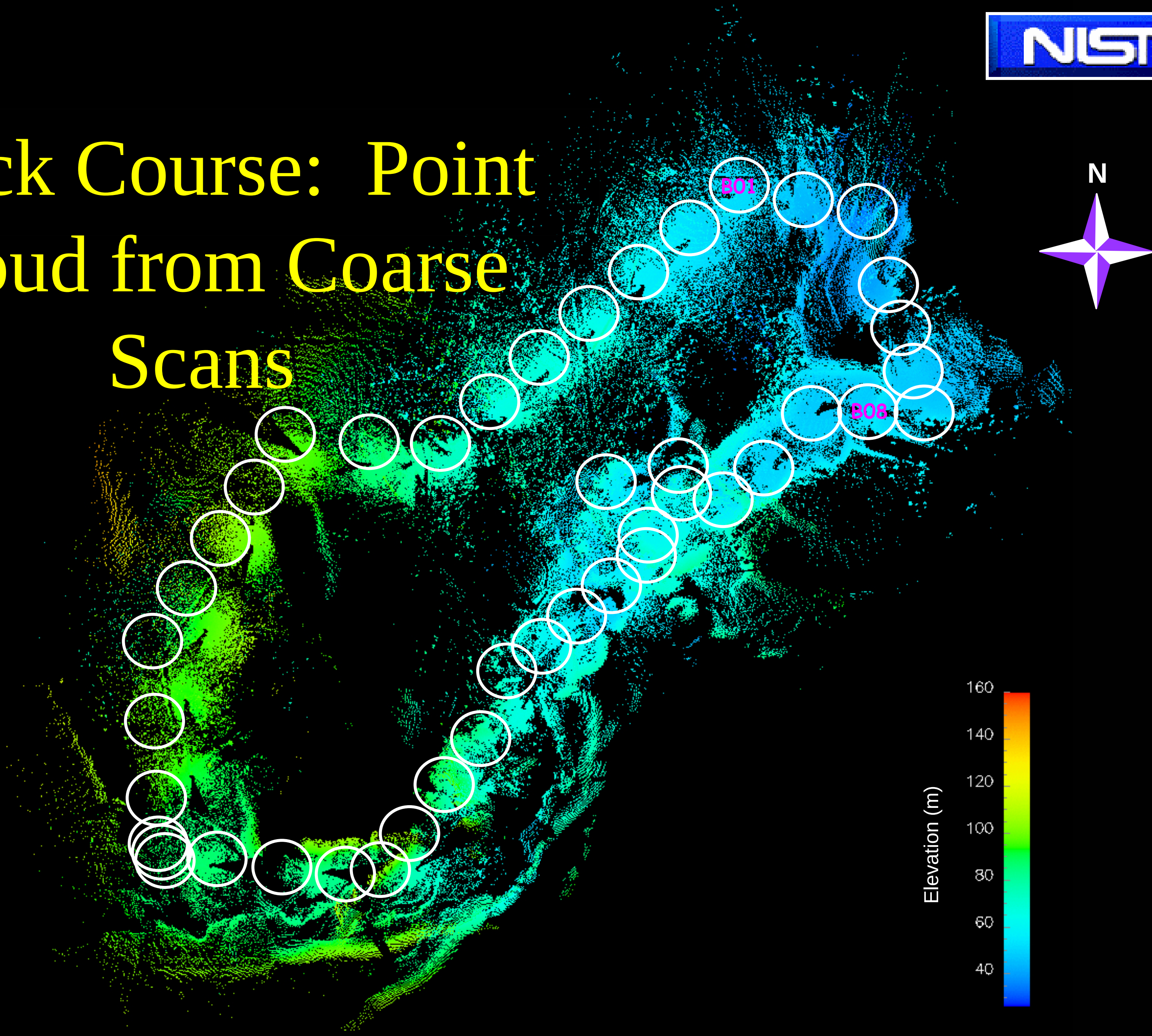


GENERAL DYNAMICS Robotic Systems

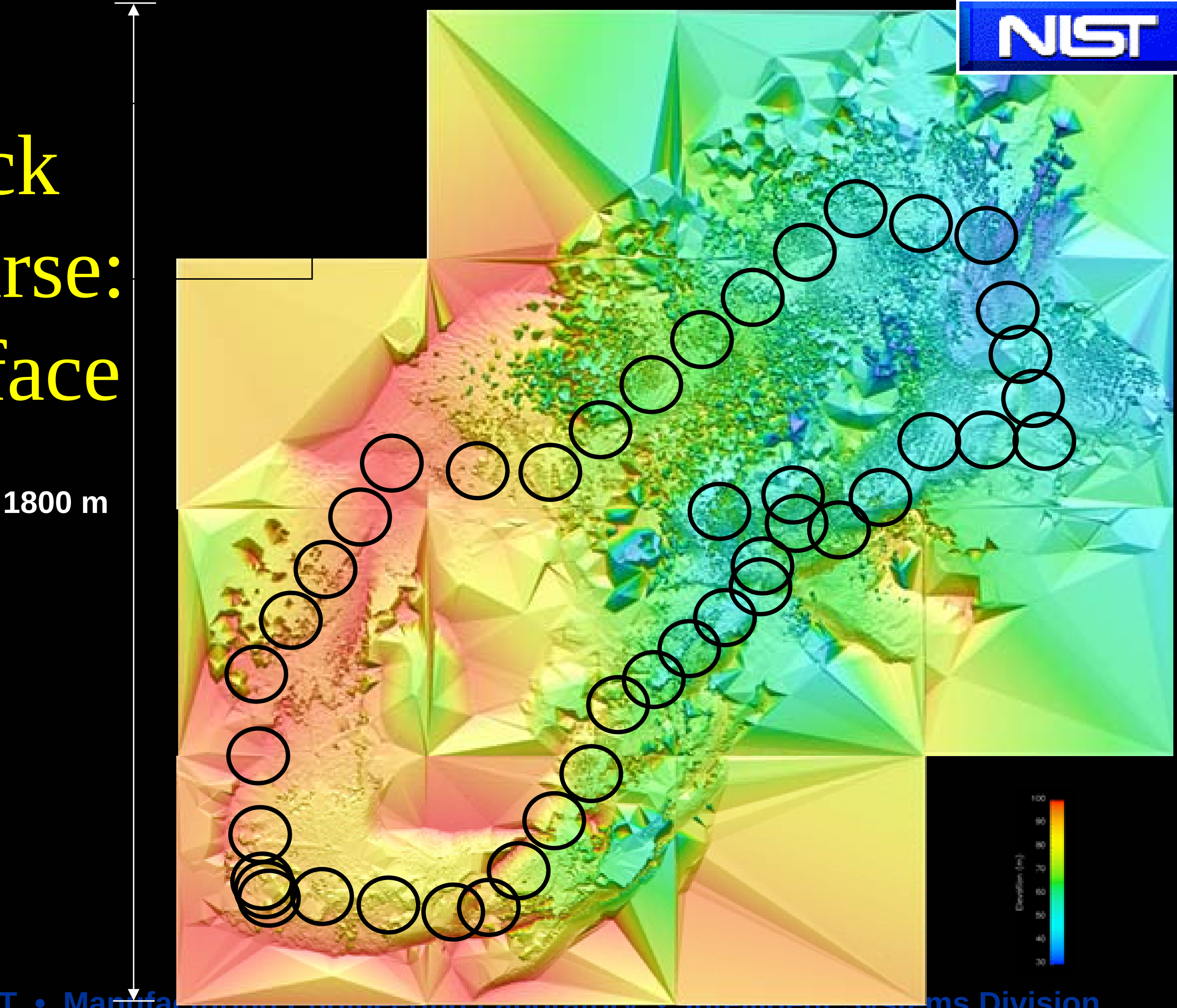
ROBOTIC RESEARCH

NIST

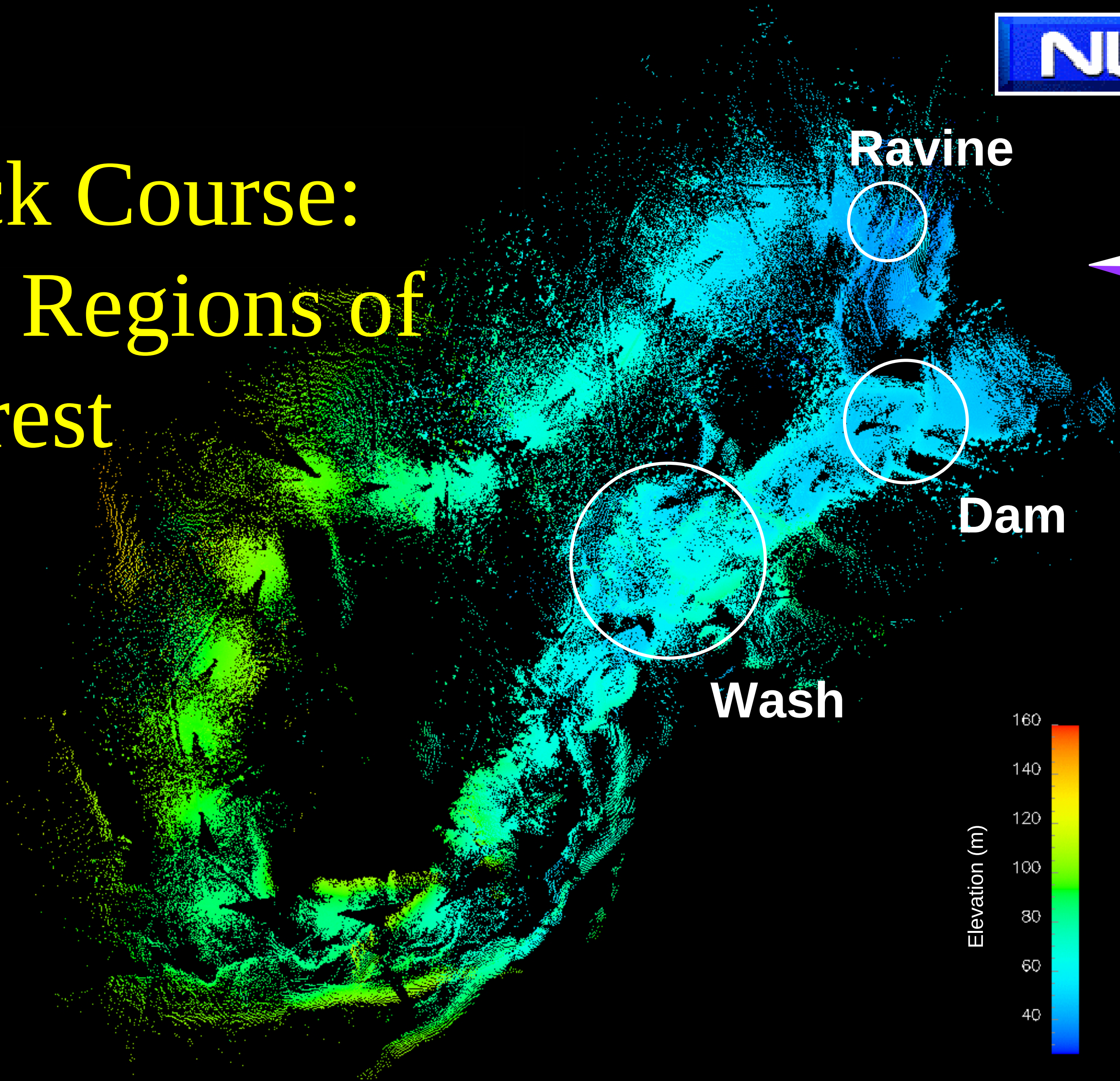
Black Course: Point Cloud from Coarse Scans



Black Course: Surface

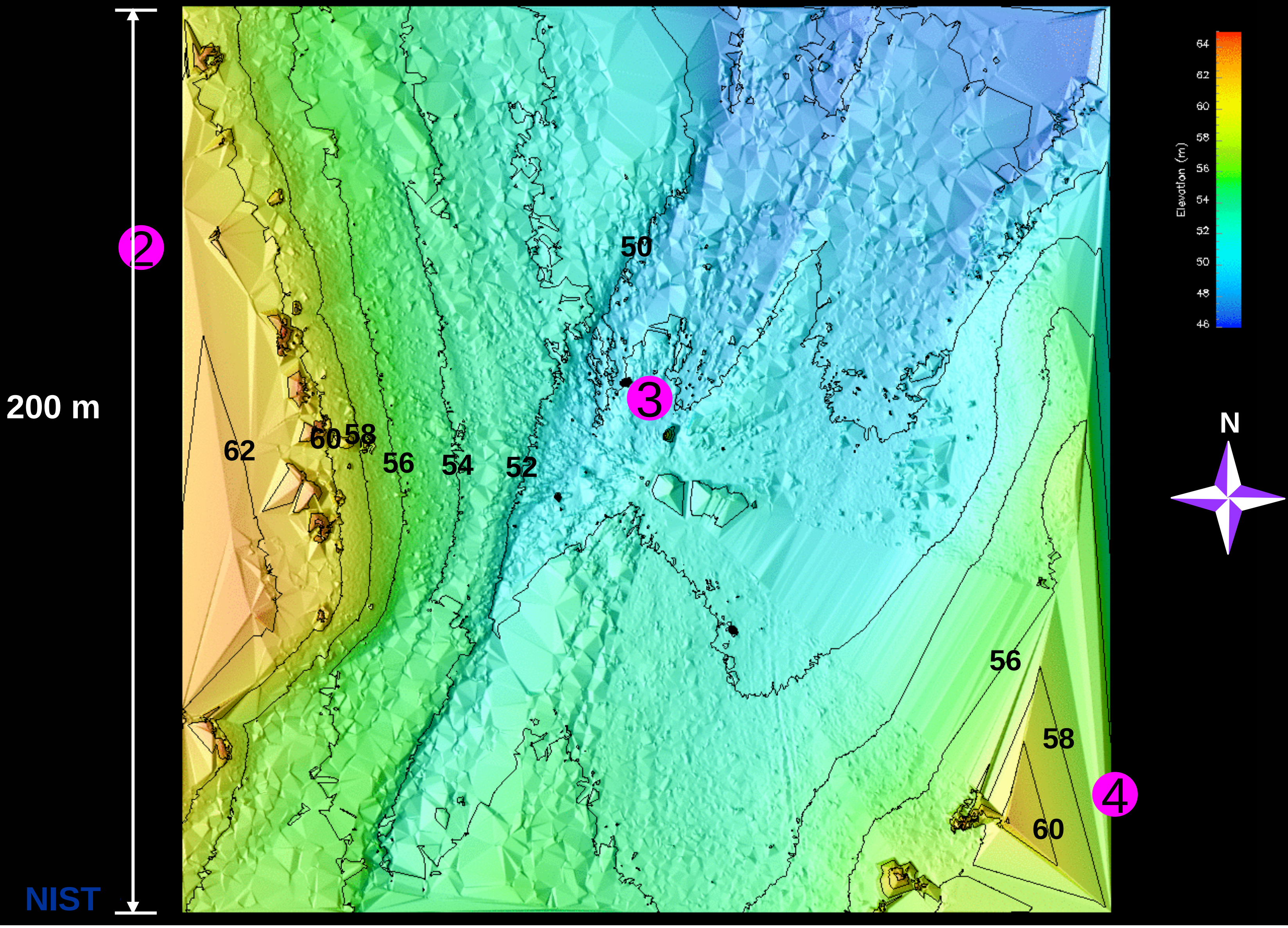


Black Course: Regions of Interest



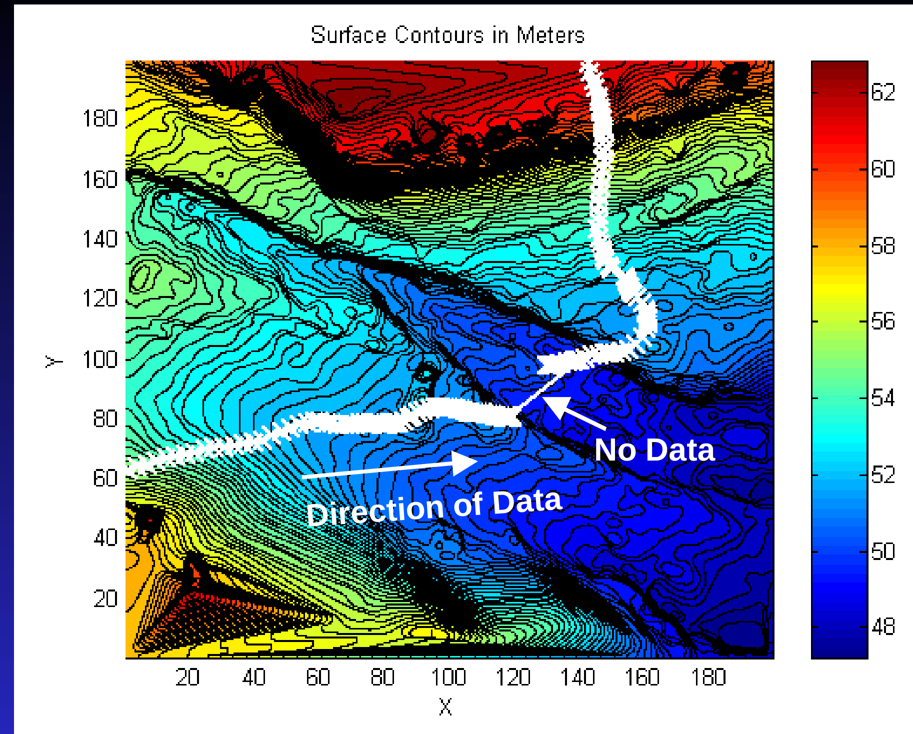
Ravine

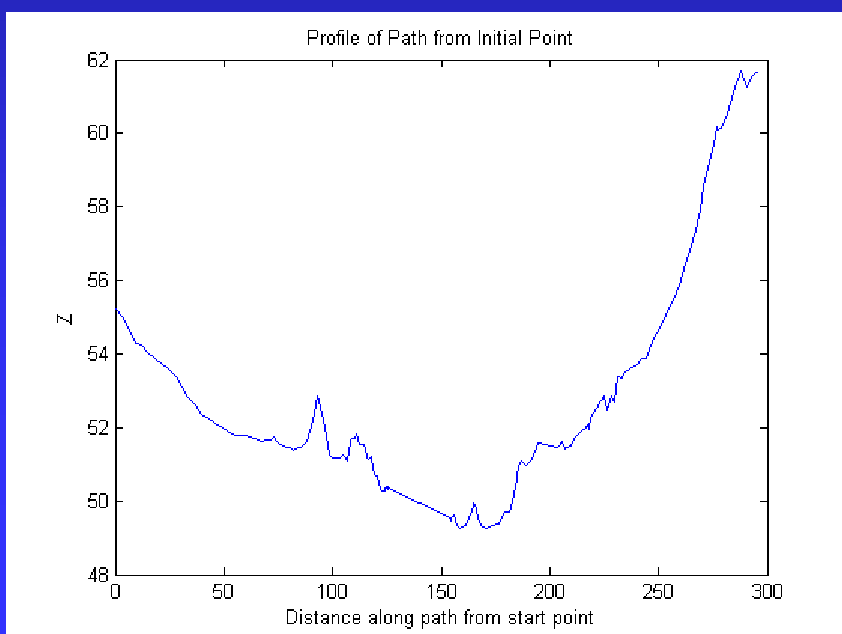
200x200 m, 16cm grid size, Overhead View

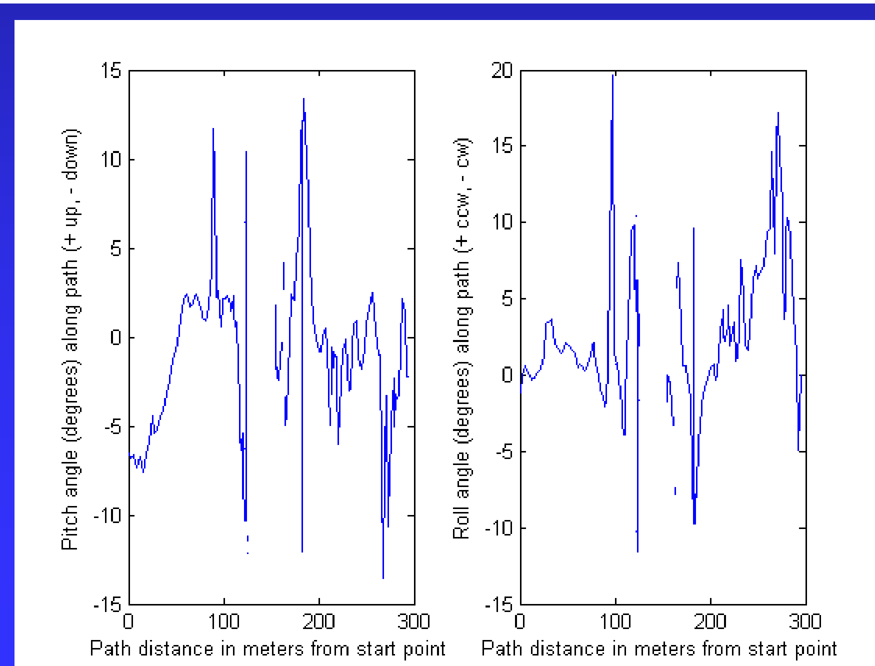


Estimated Pitch and Roll for Ravine1 200 x 200 m

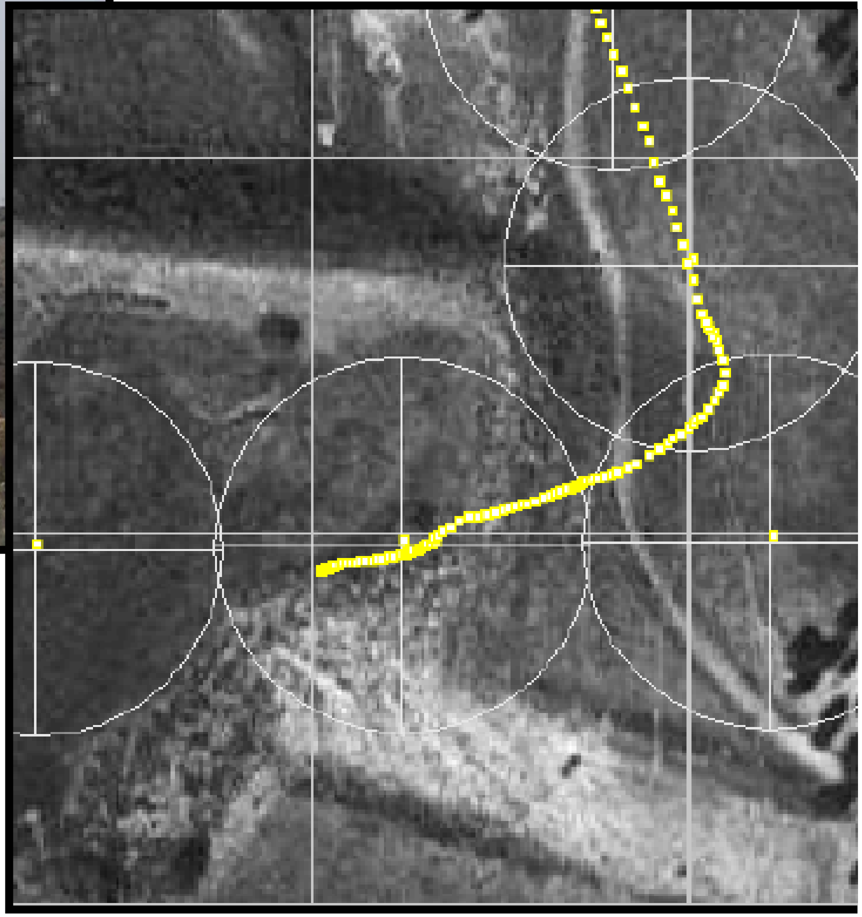
- Surface contour intervals set @ 0.2 m.
- Path data begins at approximately (0, 60) and proceeds to the right.
- Note gap in the path data leads to a gap in the roll and pitch plots.





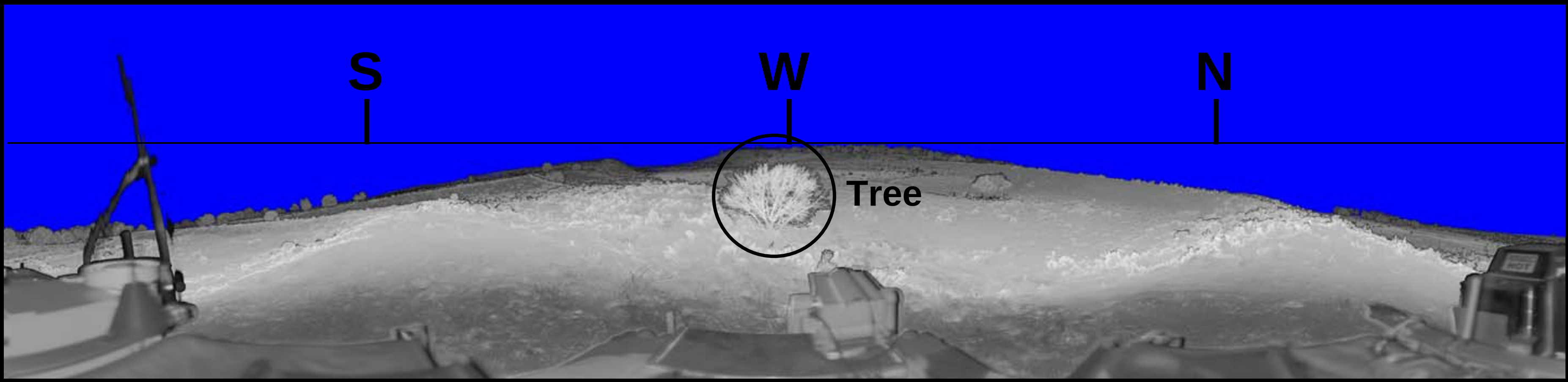


E-STOP 94 on the Dam



E-Stop 94 on the Dam

View Point 2 LADAR intensity image

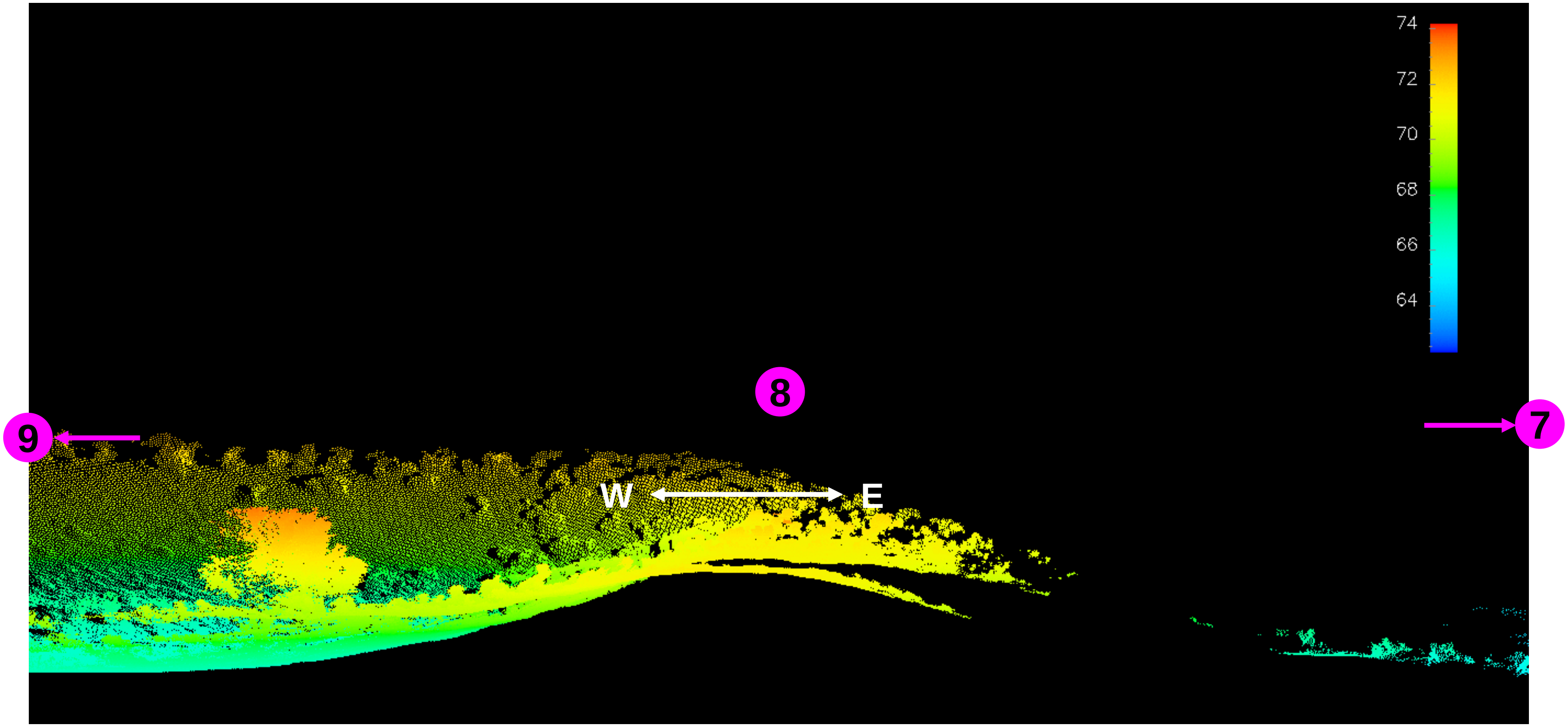


CCD Camera Image composite

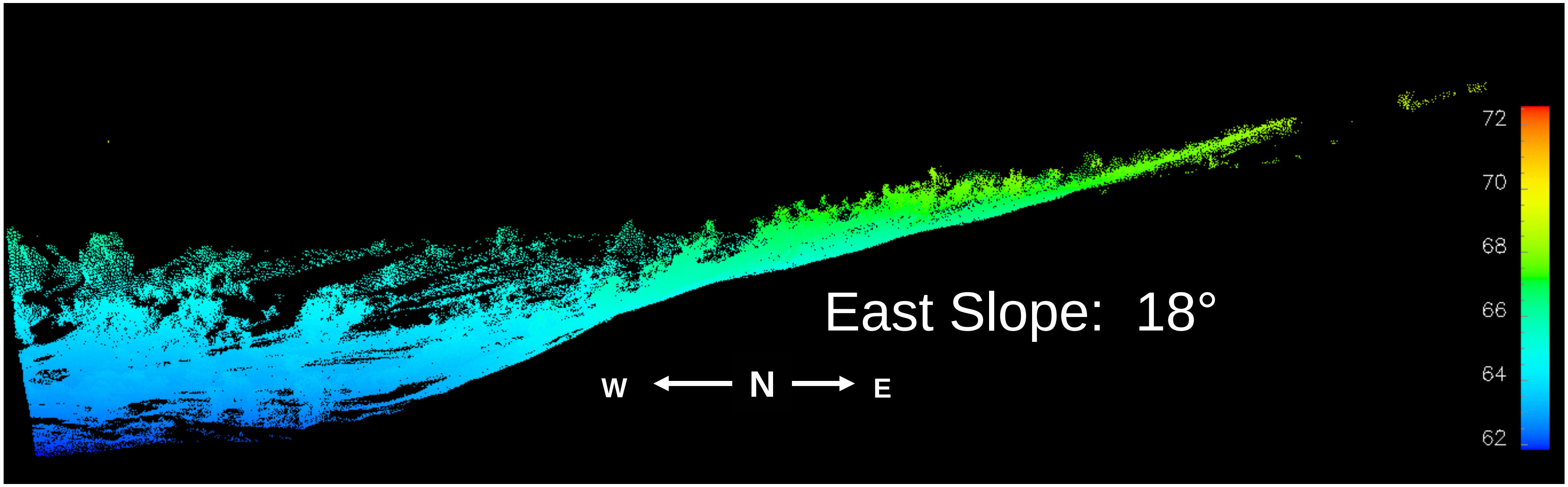
E-Stop 94

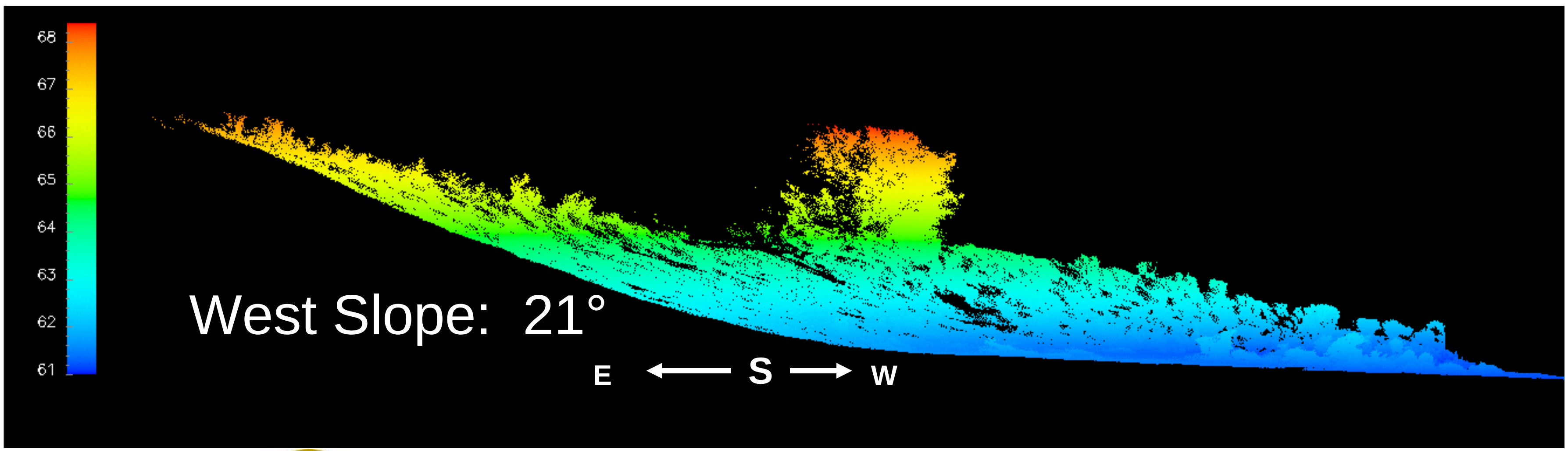
View Point 2 Looking Northward

X-section showing slopes of dam

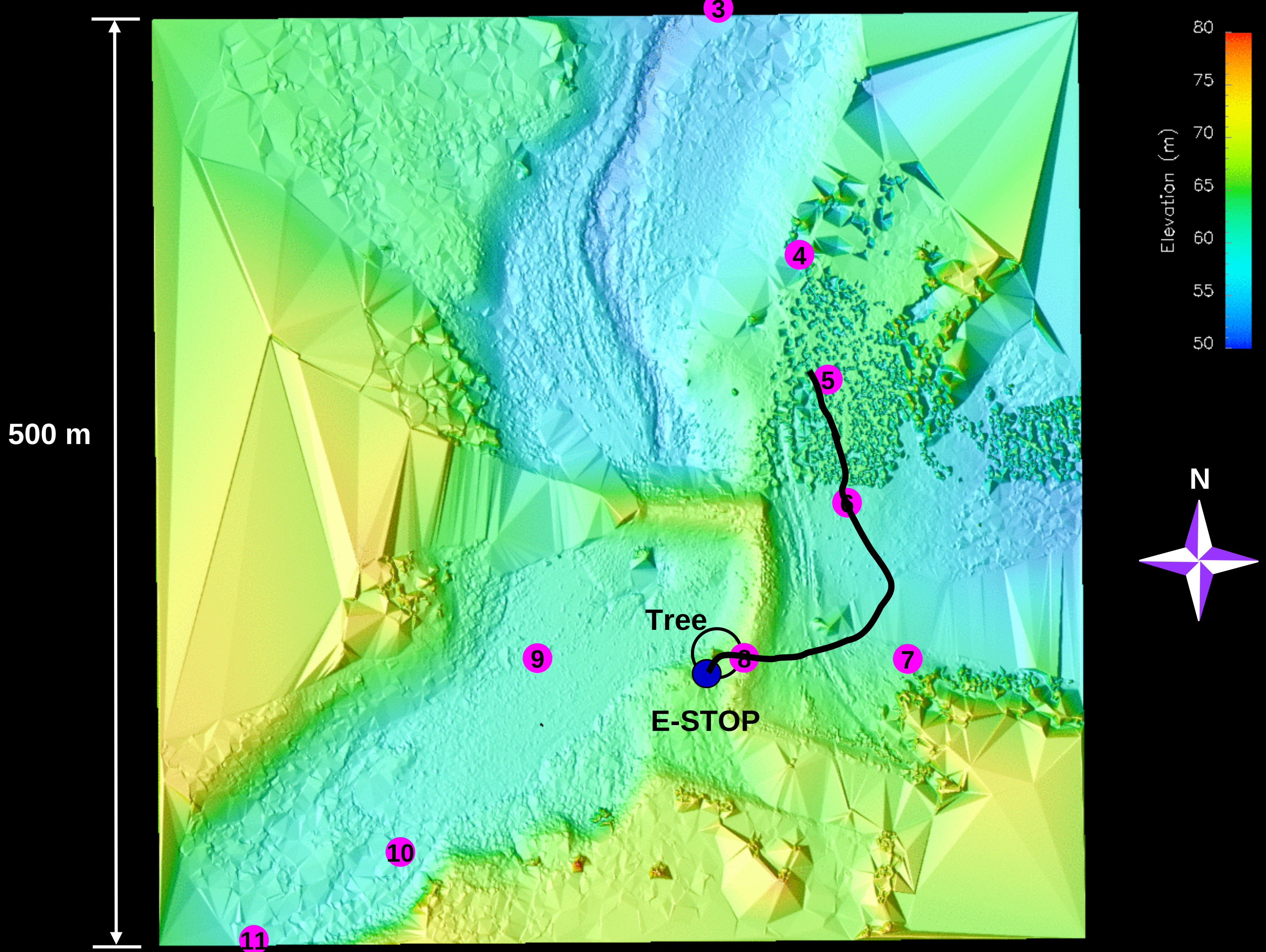


Ground Slope on the Dam



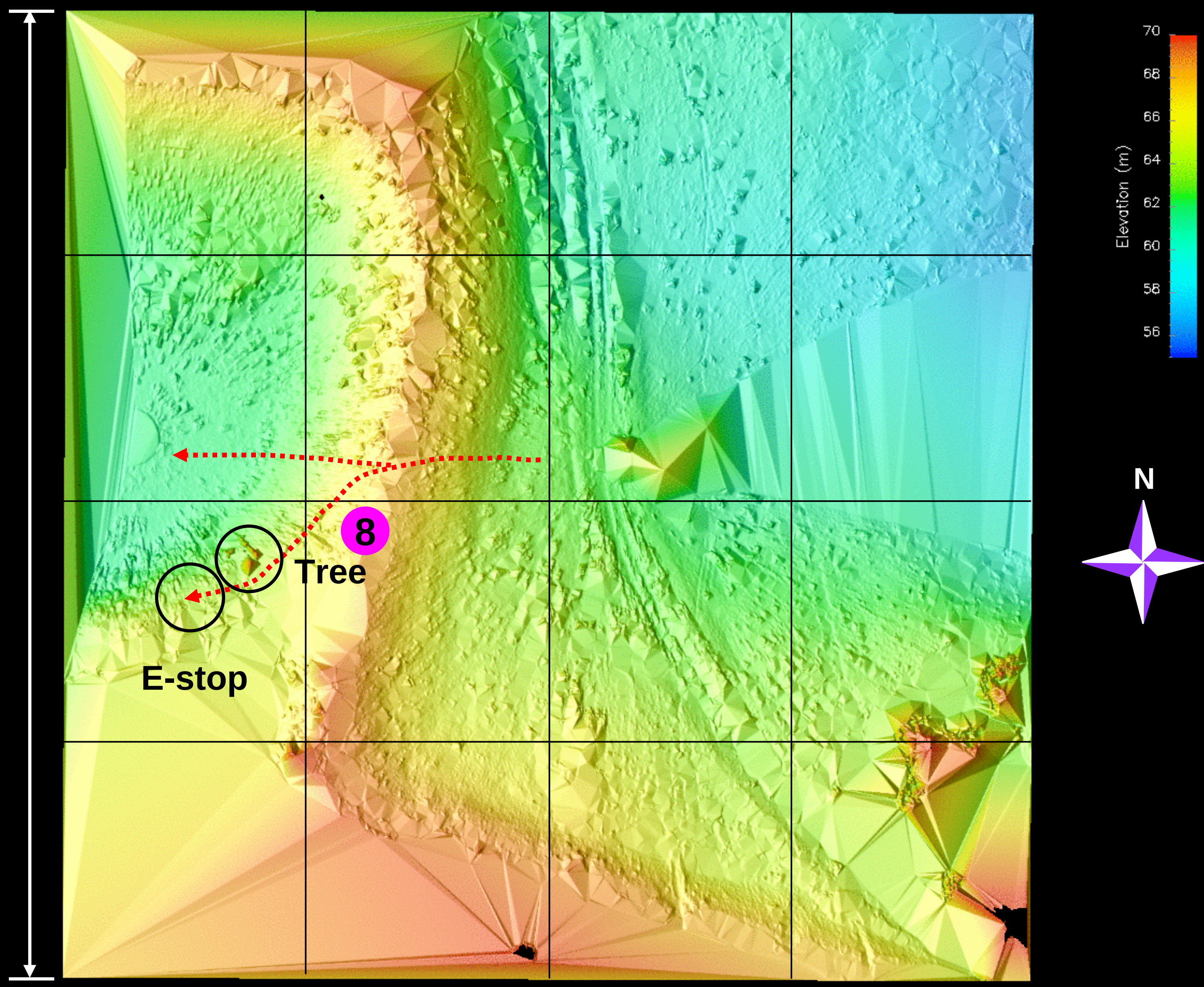


E-STOP 94 on the Dam

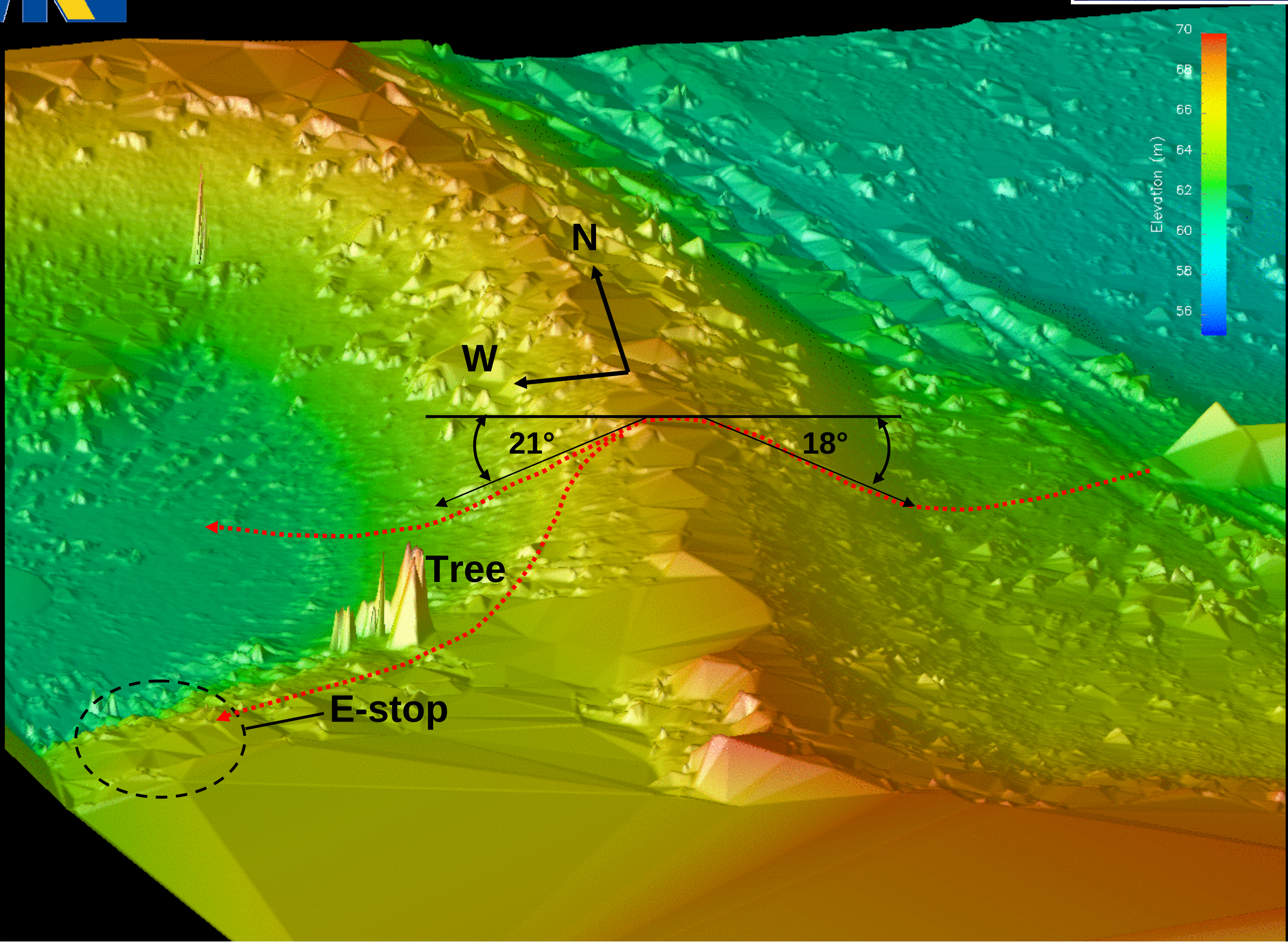


E-STOP 94 on the Dam

150 m



E-STOP 94 on the Dam



Terrain Analysis Using High Performance INS/GPs

ARL/NIST HMMWV

at Tooele Army Depot

Dec. 9-13, 2002

Harry Scott, Steve Legowik, Mike Shneier, Tsai Hong, Tommy Chang,

Harry Scott, Steve Legowik, Gerry Cheok, Chuck Giauque

Intelligent Systems Division

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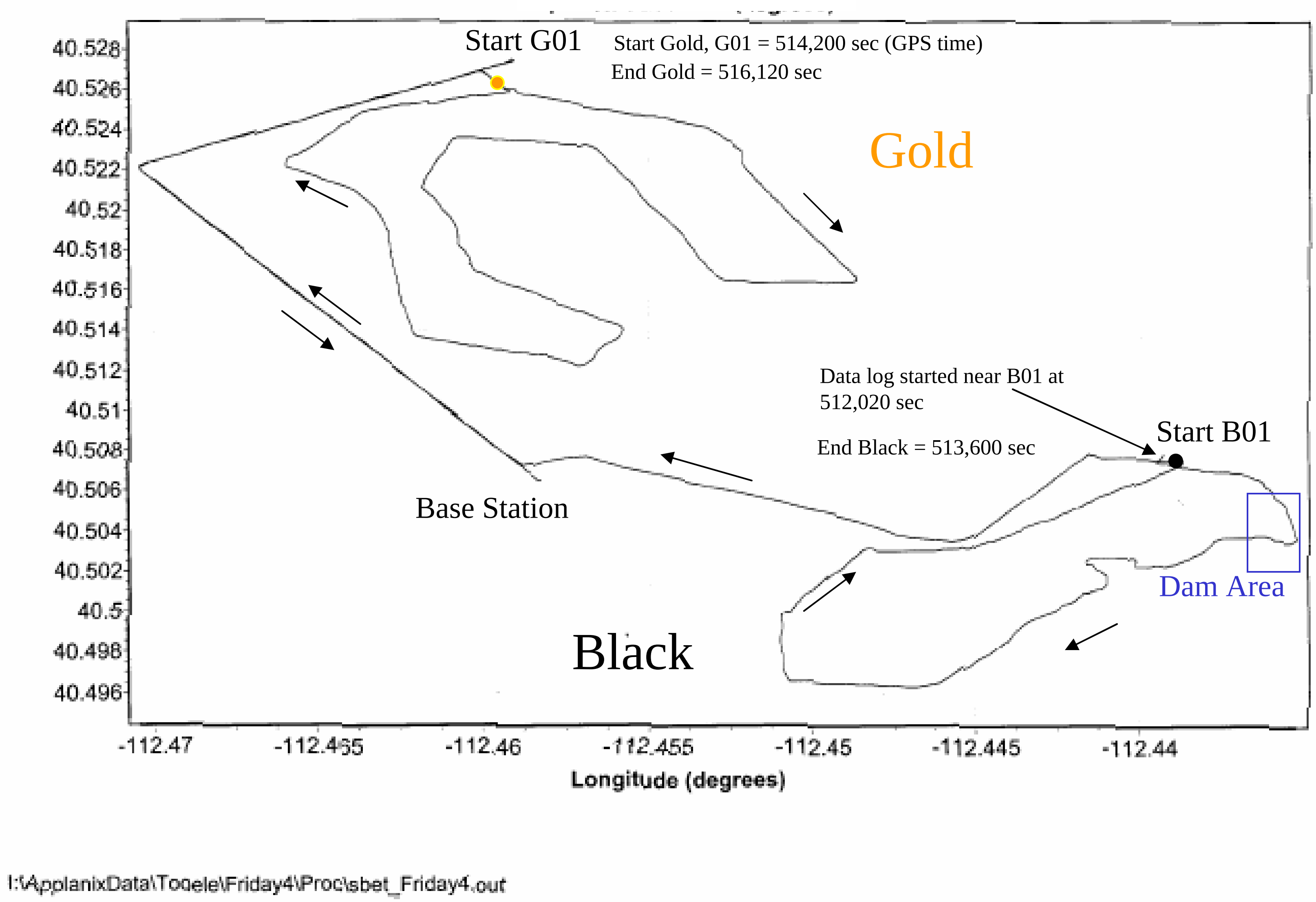
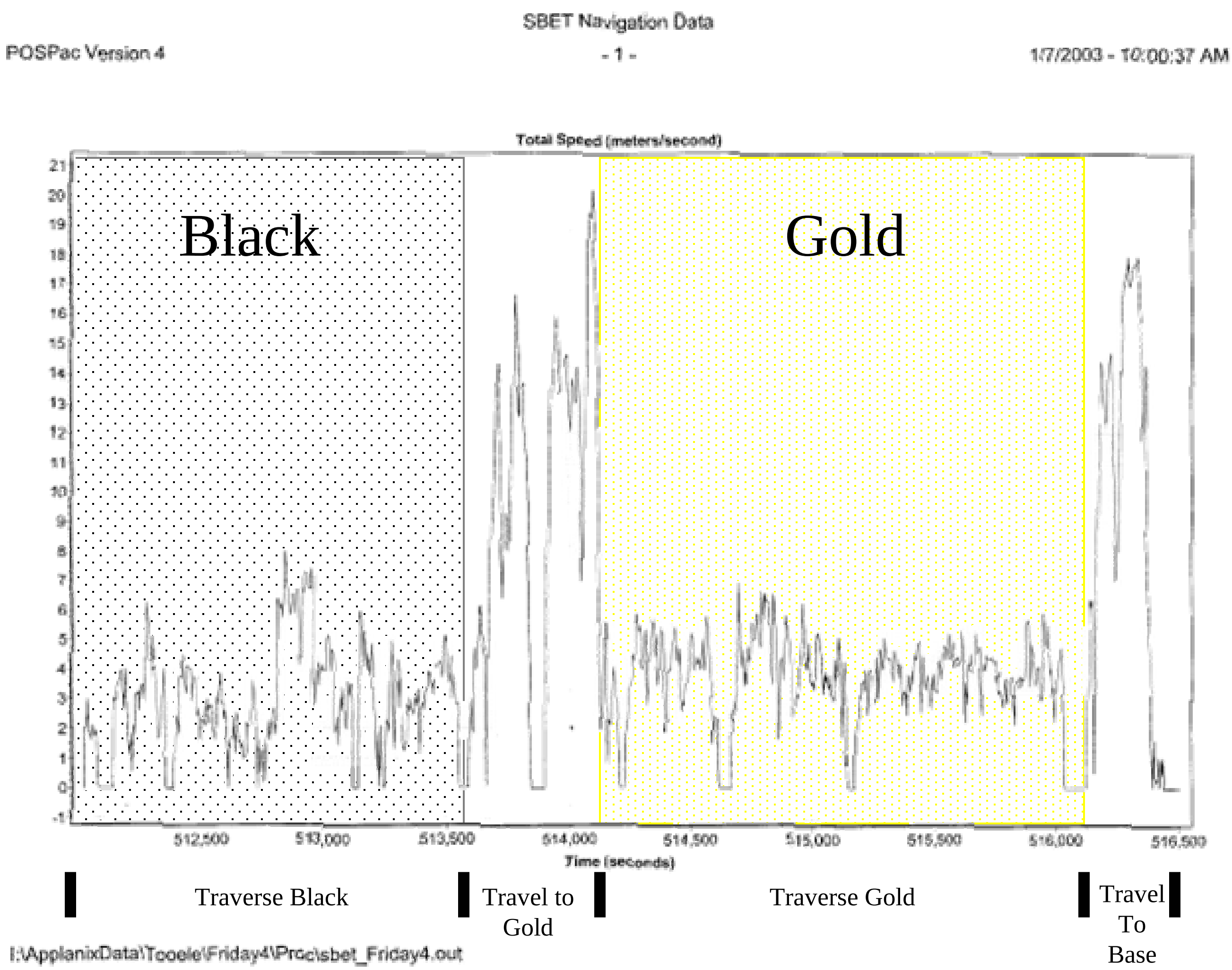
CW around Black then CW around Gold

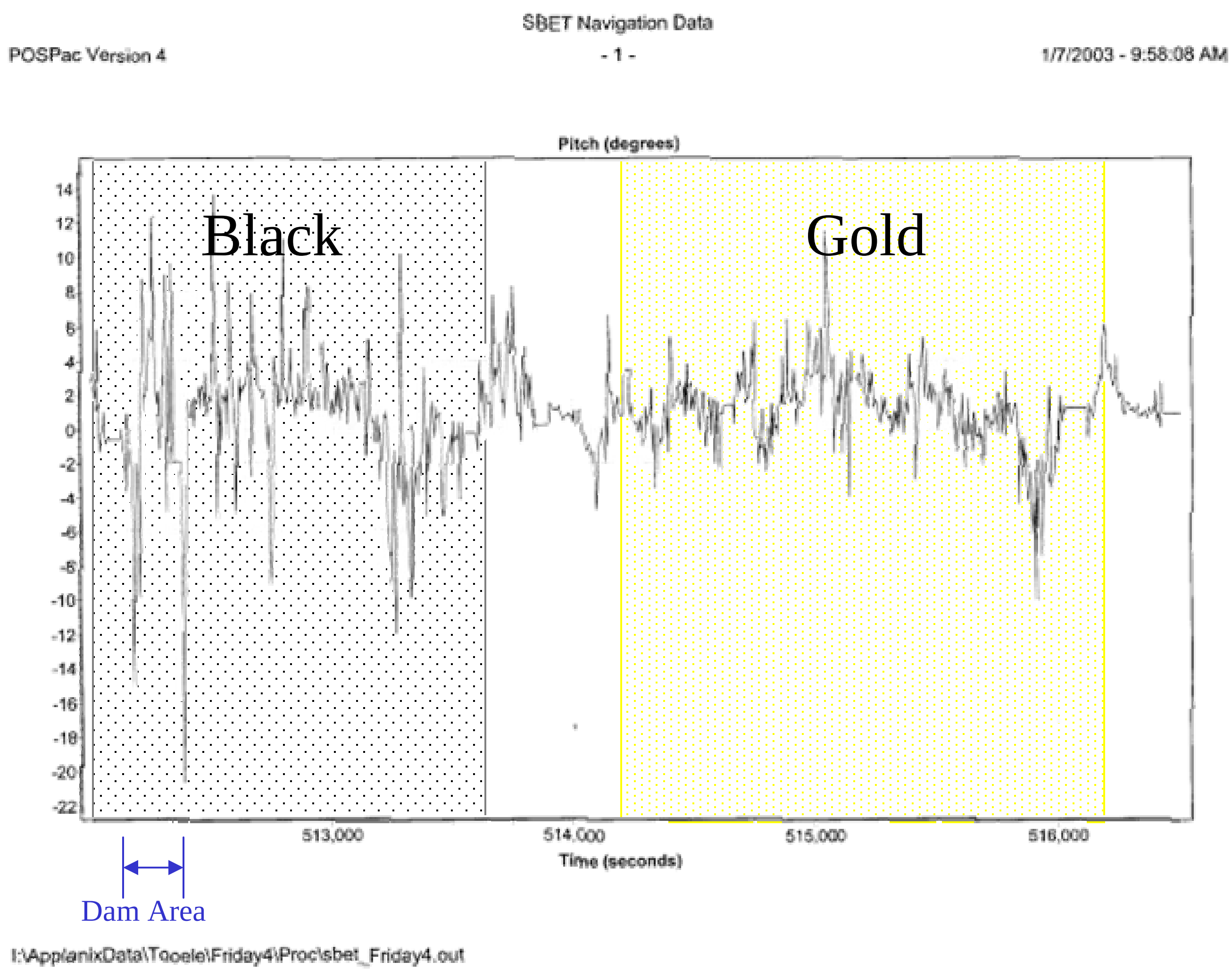


Speed

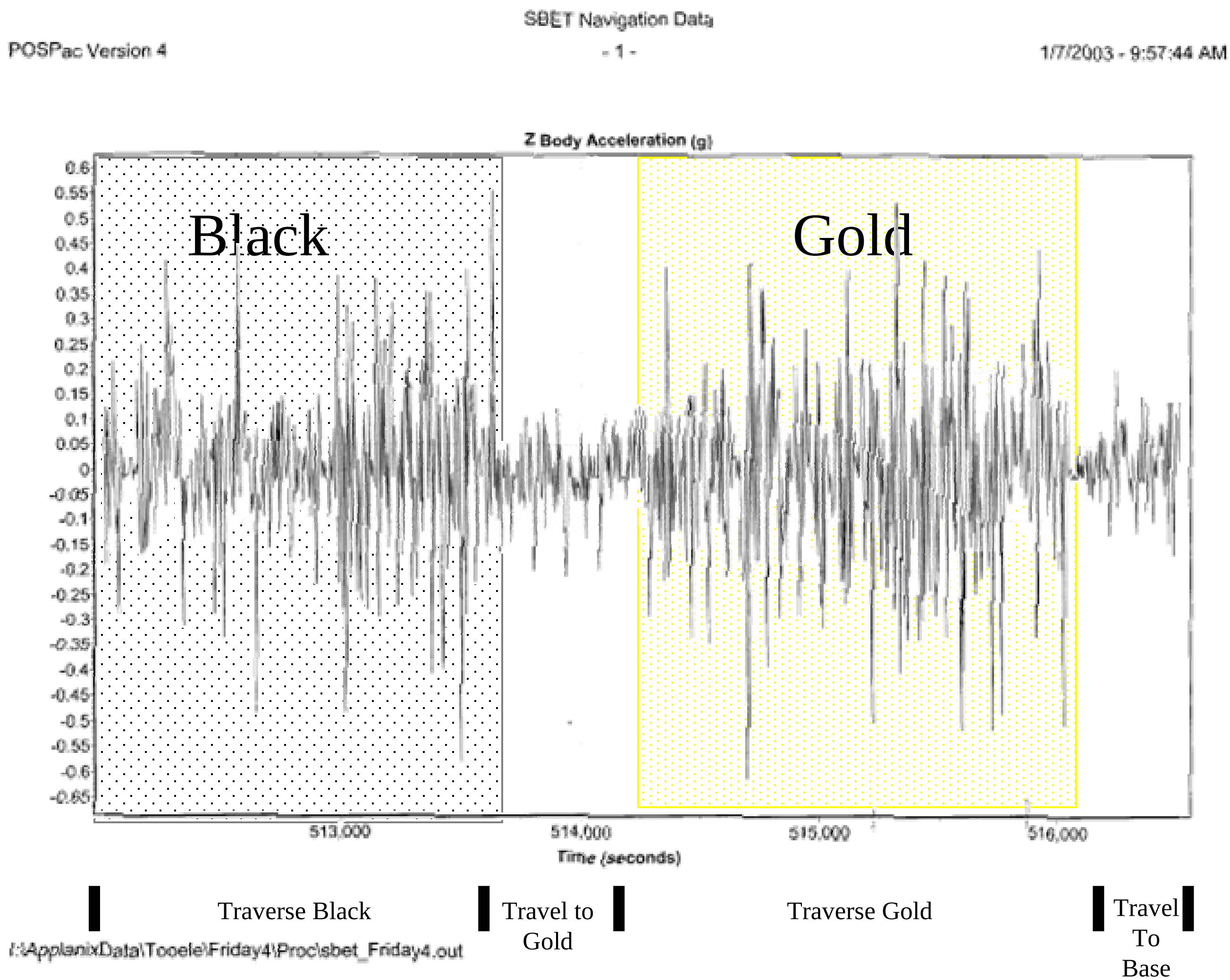


SBET Navigation Data
POSPac Version 4
- 1 -
1/7/2003 - 10:00:37 AM
Total Speed (meters/second)
Black
Gold
Time (seconds)
Traverse Black
Travel to Gold
Traverse Gold
Travel To Base
I:\ApplanixData\Tooele\Friday4\Proc\sbet_Friday4.out

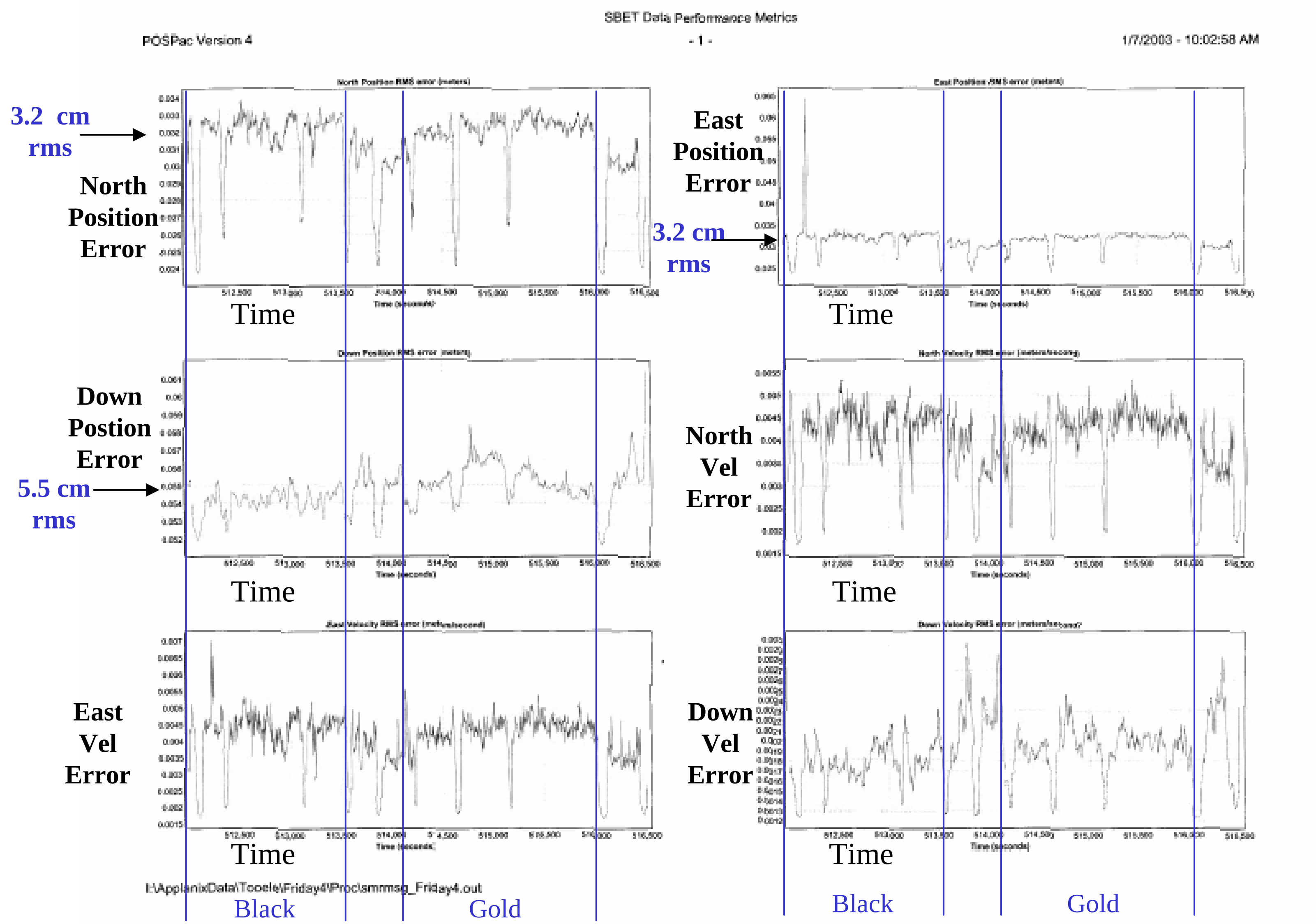
Pitch

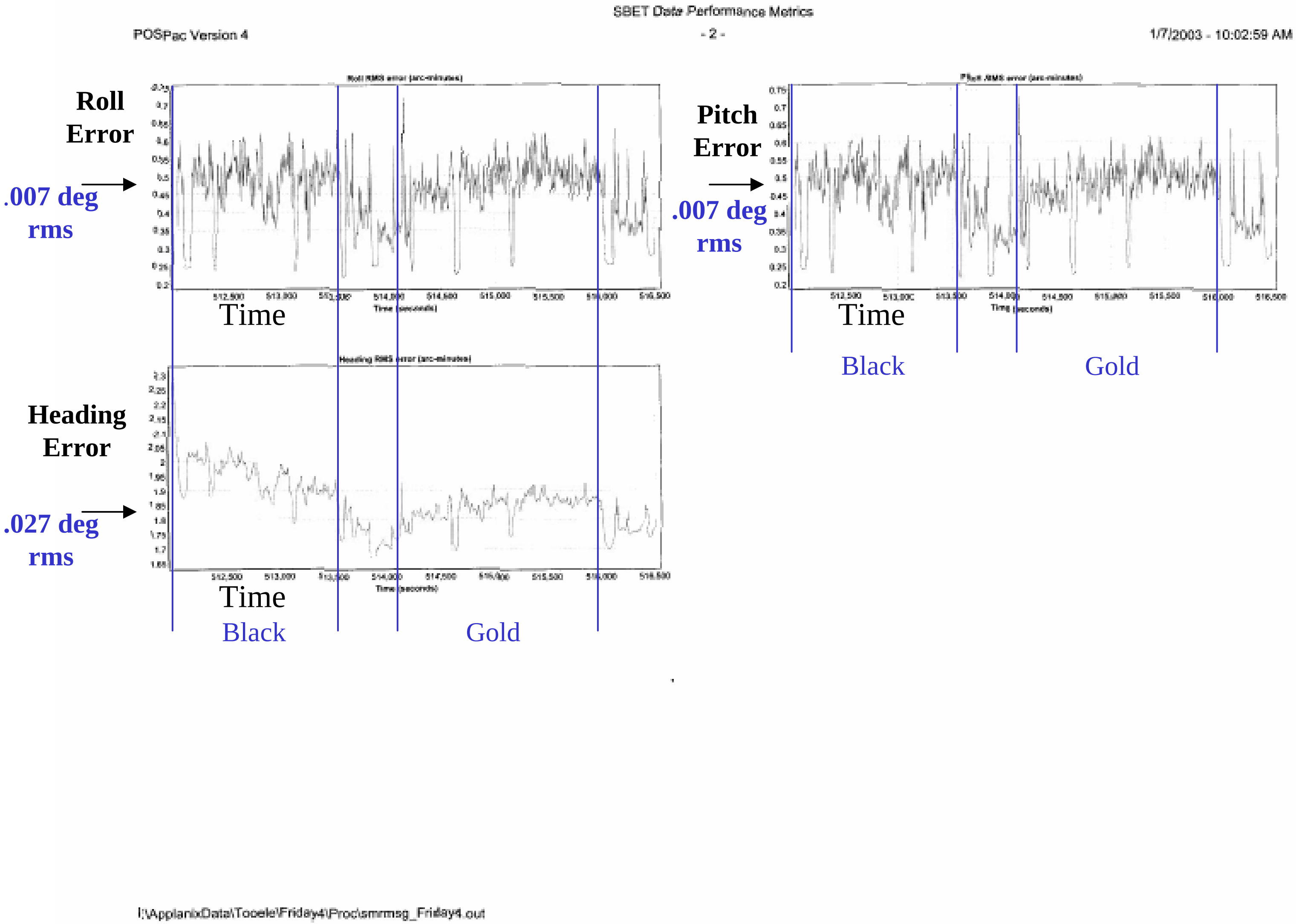

SBET Navigation Data
POSPac Version 4
- 1 -
1/7/2003 - 9:58:08 AM
Pitch (degrees)
Black
Gold
14
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
513,000
514,000
515,000
516,000
Time (seconds)
Dam Area
I:\ApplanixData\Tooele\Friday4\Proc\sbet_Friday4.out

Z (vertical) Acceleration



Nav Performance Data

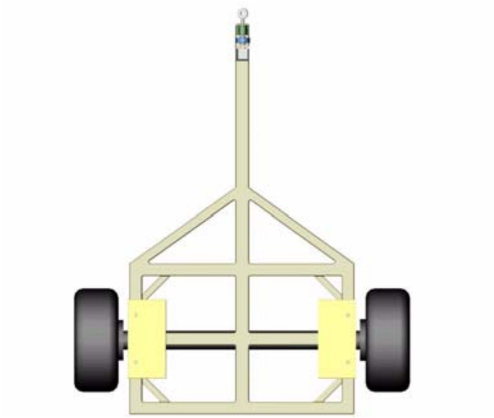




SBET Data Performance Metrics
POSPac Version 4
- 2 -
1/7/2003 - 10:02:59 AM
Roll Error
.007 deg rms
Time
Pitch Error
.007 deg rms
Time
Black
Gold
Heading Error
.027 deg rms
Time
Black
Gold
I:\ApplanixData\Tooele\Friday4\Proc\smrmsg_Friday4.out

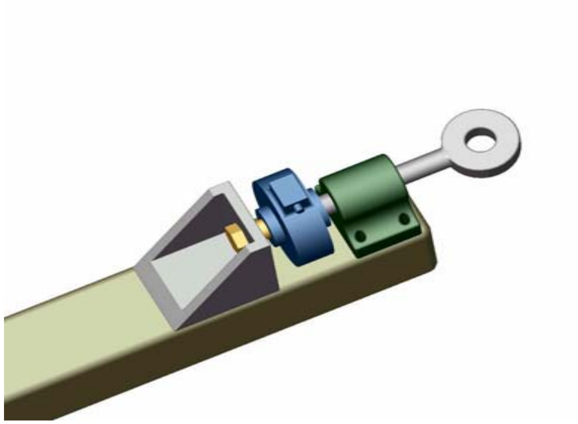
TARDEC Instrumented Trailer for Measurement of Soil Mechanics

- Features of TARDEC Trailer:
  - Load cell/strain gage on trailer tongue with signal conditioning
  - Electronic braking/micro-processor controlled (for rolling resistance and ground friction measurements)
  - Variable load on trailer axle (bolted steel plates – matches XUV loading)
  - XUV tires and 12” ground clearance on trailer (highly mobile)



Top View

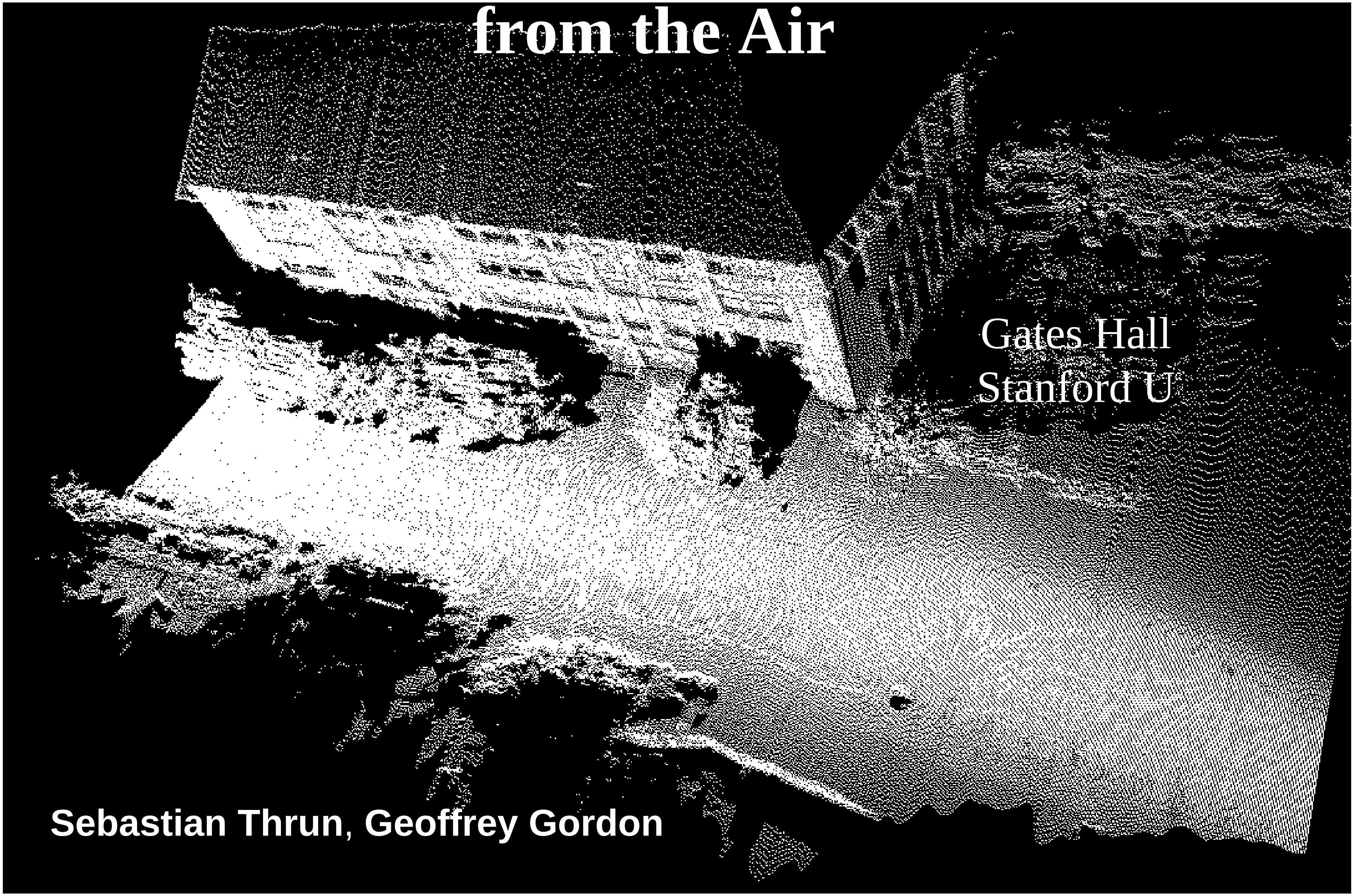
Isometric View



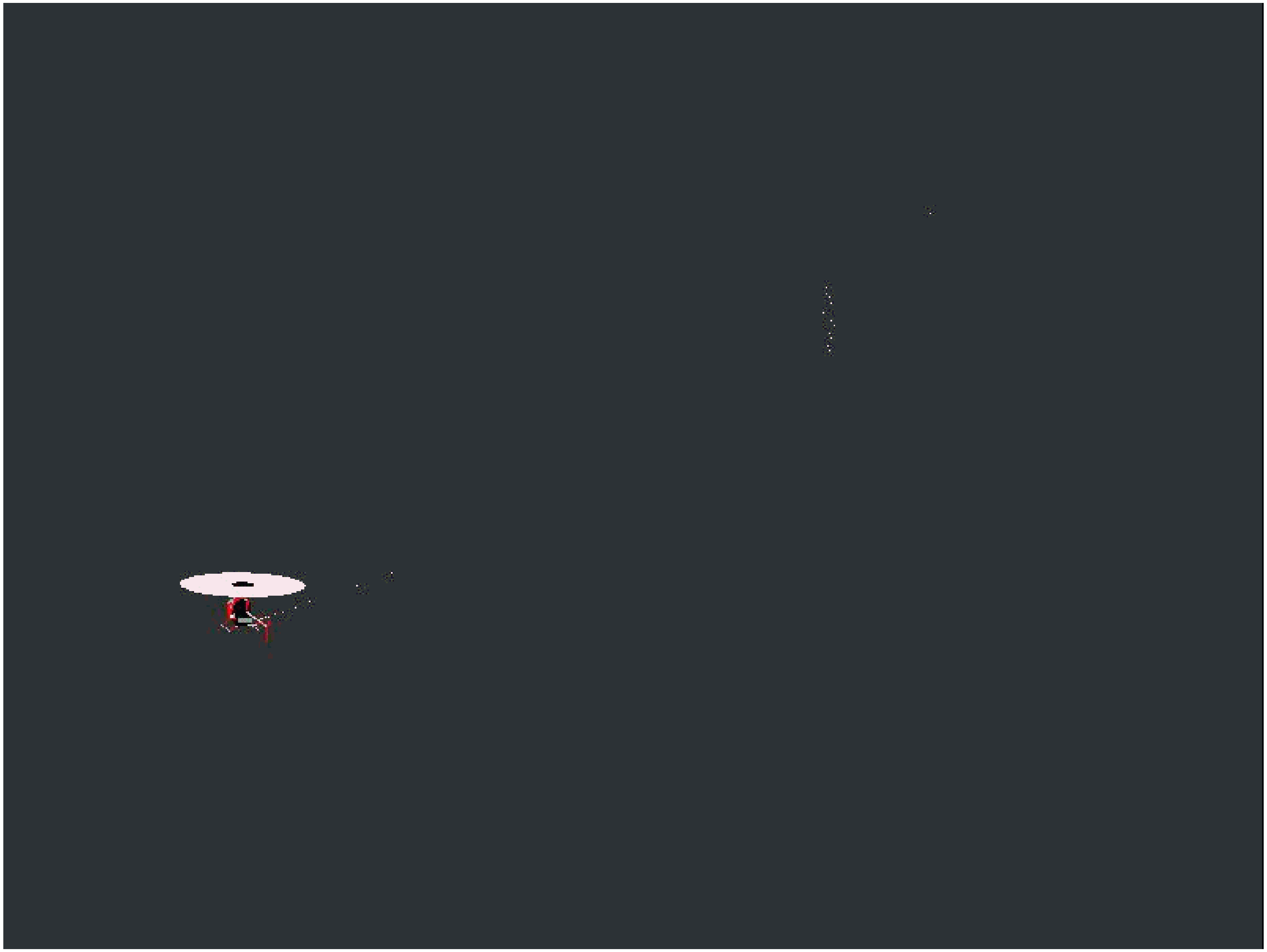
Trailer Hitch


TARDEC Instrumented Trailer
at Tooele Army Depot

Terrain Characterization from the Air



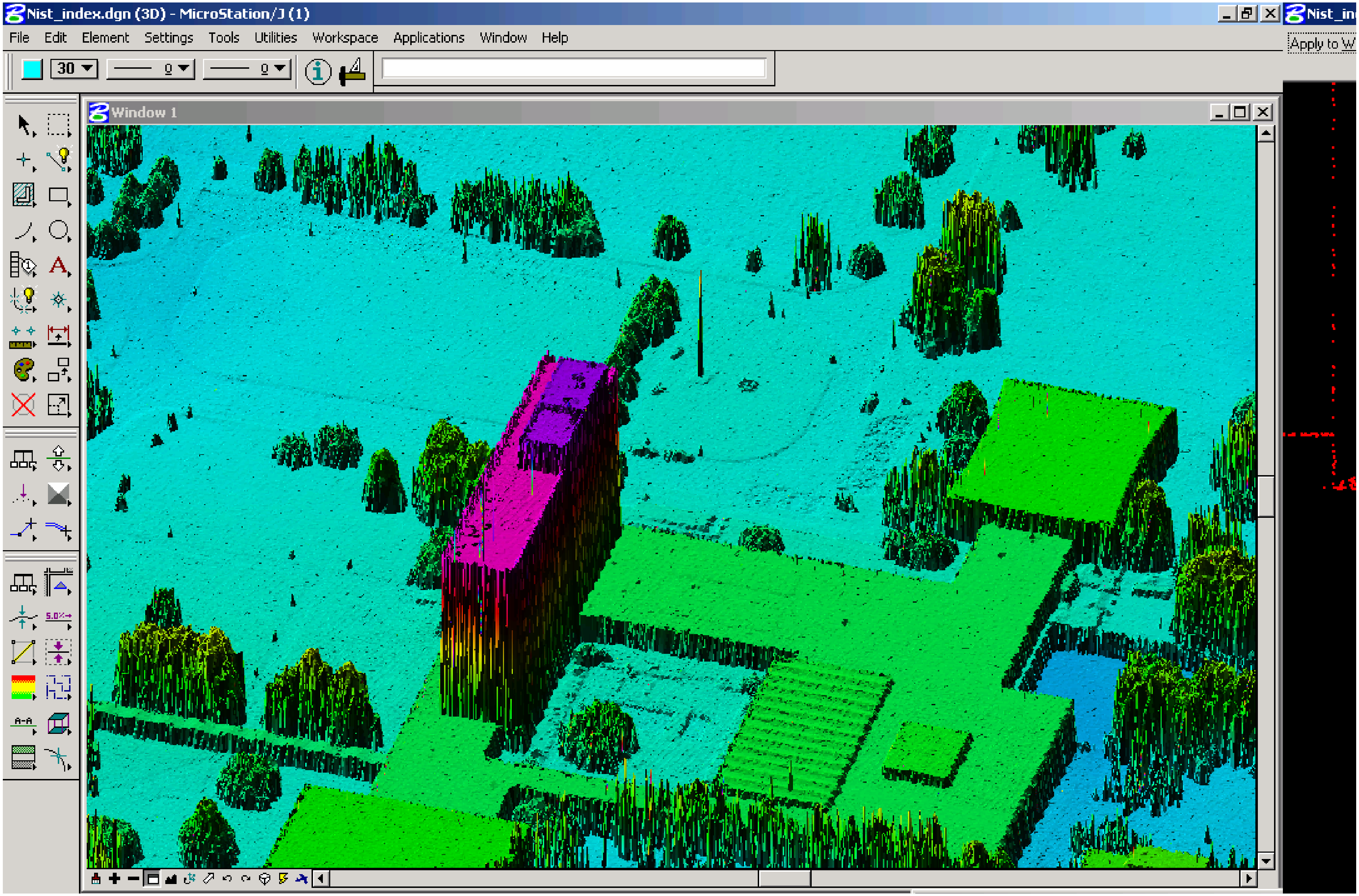
Active Volumetric Mapping



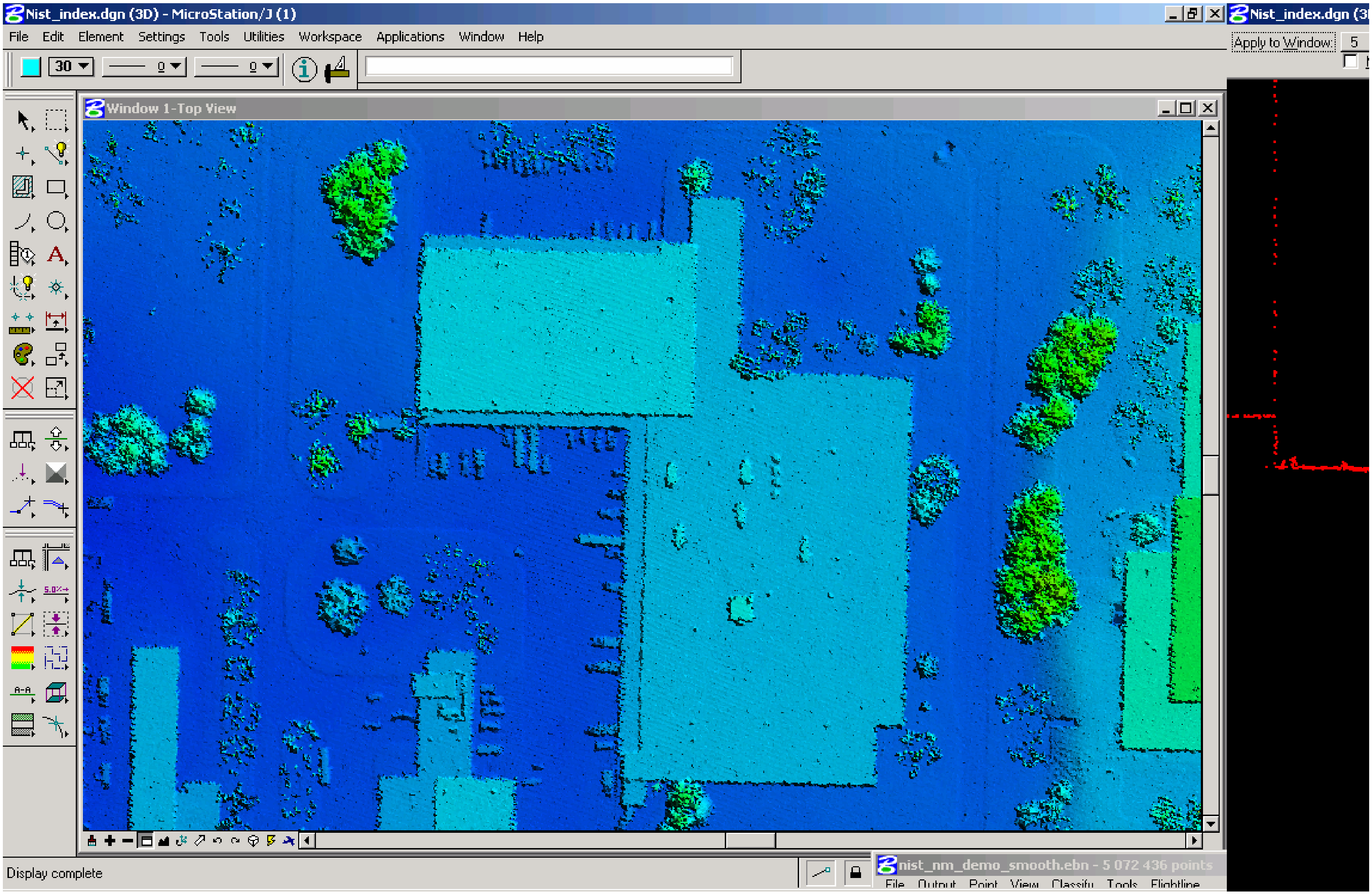
Sebastian Thrun, Geoffrey Gordon

Gates Hall, Stanford U

Ground Truth at NIST



Ground Truth at NIST



Technology Requirements for Autonomous On-Road Driving

Analysis of tasks

what? when? why? how? where?

Decomposition into levels based on

range and resolution in time & space

Analysis of knowledge requirements

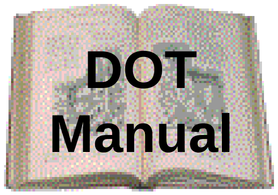
geometry, dynamics, entities, events, situations

Analysis of sensor requirements

field of view, resolution in time and space

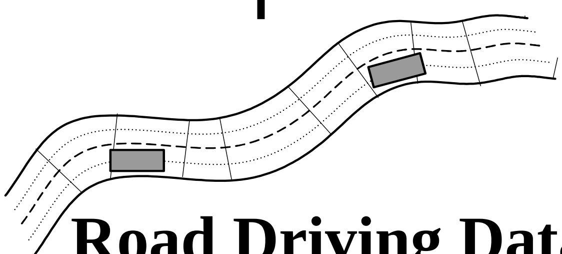
Driving Task Analysis

1) Analyze Autonomous Driving Tasks & Develop a Task Architecture



Task Analysis

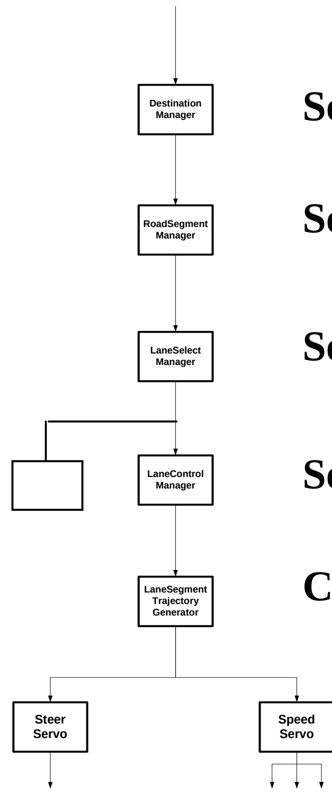
+



Road Driving Data Representations

=>

Gaze Control



Selects Destination
2 hour plan

Selects Road Segments
10 min plans

Selects Lane
1 min plans

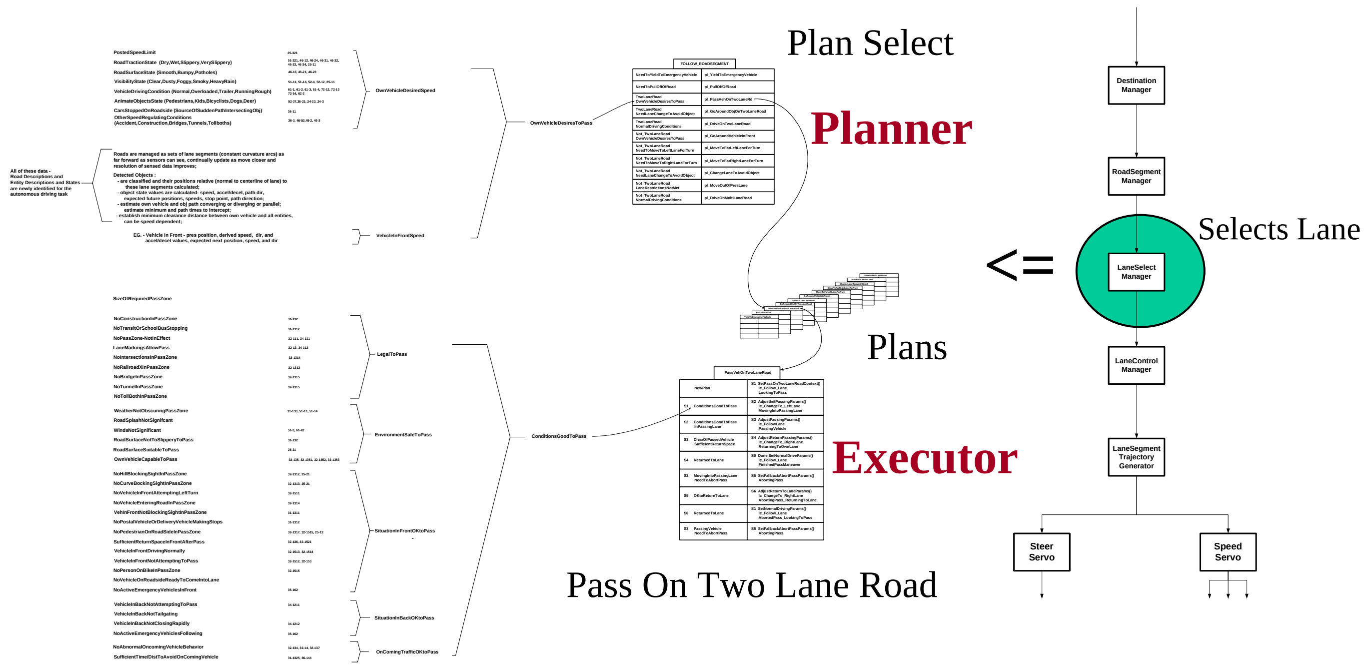
Selects Pos & Speed In Lane
10 sec plans

Creates Trajectory
1 sec plans

Servos Steer & Speed
100 ms plans

Driving Task Analysis

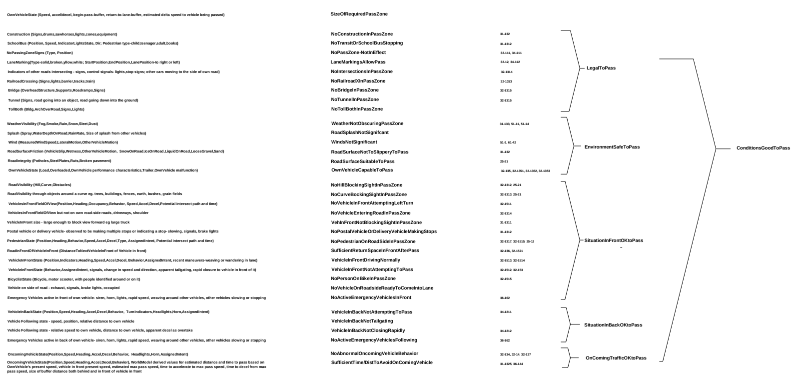
2) From task architecture, derive finite-state automata that encode task behaviors



World Model Situation | **Value Judgment** | **Behavior Generation**

Driving Task Analysis

3) From FSMs, derive decision criteria and Value Judgments



World Model Situation **Value Judgment**

Pass on Two Lane Road

NewPlan	S1 SetPassOnTwoLaneRoadContext() lc_Follow_Lane LookingToPass
S1 ConditionsGoodToPass	S2 AdjustInitPassingParams() lc_ChangeTo_LeftLane MovingIntoPassingLane
S2 ConditionsGoodToPass InPassingLane	S3 AdjustPassingParams() lc_FollowLane PassingVehicle
S3 ClearOfPassedVehicle SufficientReturnSpace	S4 AdjustReturnPassingParams() lc_ChangeTo_RightLane ReturningToOwnLane
S4 ReturnedToLane	S0 Done SetNormalDriveParams() lc_Follow_Lane FinishedPassManeuver
S2 MovingIntoPassingLane NeedToAbortPass	S5 SetFallbackAbortPassParams() AbortingPass
S5 OKtoReturnToLane	S6 AdjustReturnToLaneParams() lc_ChangeTo_RightLane AbortingPass_ReturningToLane
S6 ReturnedToLane	S1 SetNormalDrivingParams() lc_Follow_Lane AbortedPass_LookingToPass
S3 PassingVehicle NeedToAbortPass	S5 SetFallbackAbortPassParams() AbortingPass

Plan

Driving Task Analysis

4) Derive dependencies on World Model Situations

NoConstructionInPassZone
NoTransitOrSchoolBusStopping
NoPassZone-NotInEffect
LaneMarkingsAllowPass
NoIntersectionsInPassZone
NoRailroadXInPassZone
NoBridgeInPassZone
NoTunnelInPassZone
NoTollBothInPassZone

LegalToPass

WeatherNotObscuringPassZone
RoadSplashNotSignifcant
WindsNotSignificant
RoadSurfaceNotToSlipperyToPass
RoadSurfaceSuitableToPass
OwnVehicleCapableToPass

EnvironmentSafeToPass

NoHillBlockingSightInPassZone
NoCurveBockingSightInPassZone
NoVehicleInFrontAttemptingLeftTurn
NoVehicleEnteringRoadInPassZone
VehInFrontNotBlockingSightInPassZone
NoPostalVehicleOrDeliveryVehicleMakingStops
NoPedestrianOnRoadSideInPassZone
SufficientReturnSpaceInFrontAfterPass
VehicleInFrontDrivingNormally
VehicleInFrontNotAttemptingToPass
NoPersonOnBikeInPassZone
NoVehicleOnRoadsideReadyToComeIntoLane
NoActiveEmergencyVehiclesInFront

SituationInFrontOKtoPass

NoConstructionInPassZone
NoTransitOrSchoolBusStopping
NoPassZone-NotInEffect
LaneMarkingsAllowPass

SituationInBackOKtoPass

NoIntersectionsInPassZone
NoRailroadXInPassZone

OnComingTrafficOKtoPass

ConditionsGoodToPass

PassVehOnTwoLaneRoad

NewPlan	S1 SetPassOnTwoLaneRoadContext() lc_Follow_Lane LookingToPass
S1 ConditionsGoodToPass	S2 AdjustInitPassingParams() lc_ChangeTo_LeftLane MovingIntoPassingLane
S2 ConditionsGoodToPass InPassingLane	S3 AdjustPassingParams() lc_FollowLane PassingVehicle
S3 ClearOfPassedVehicle SufficientReturnSpace	S4 AdjustReturnPassingParams() lc_ChangeTo_RightLane ReturningToOwnLane
S4 ReturnedToLane	S0 Done SetNormalDriveParams() lc_Follow_Lane FinishedPassManeuver
S2 MovingIntoPassingLane NeedToAbortPass	S5 SetFallbackAbortPassParams() AbortingPass
S5 OKtoReturnToLane	S6 AdjustReturnToLaneParams() lc_ChangeTo_RightLane AbortingPass_ReturningToLane
S6 ReturnedToLane	S1 SetNormalDrivingParams() lc_Follow_Lane AbortedPass_LookingToPass
S3 PassingVehicle NeedToAbortPass	S5 SetFallbackAbortPassParams() AbortingPass

Plan

World Model Situation | **Value Judgment** | **Behavior Generation**

Driving Task Analysis

5) Derive World Model Knowledge requirements

NoConstructionInPassZone
NoTransitOrSchoolBusStopping
NoPassZone-NotInEffect
LaneMarkingsAllowPass
NoIntersectionsInPassZone
NoRailroadXInPassZone
NoBridgeInPassZone
NoTunnelInPassZone
NoTollBothInPassZone

LegalToPass

WeatherNotObscuringPassZone
RoadSplashNotSignifcant
WindsNotSignificant
RoadSurfaceNotToSlipperyToPass
RoadSurfaceSuitableToPass
OwnVehicleCapableToPass

EnvironmentSafeToPass

NoHillBlockingSightInPassZone
NoCurveBockingSightInPassZone
NoVehicleInFrontAttemptingLeftTurn
NoVehicleEnteringRoadInPassZone
VehInFrontNotBlockingSightInPassZone
NoPostalVehicleOrDeliveryVehicleMakingStops
NoPedestrianOnRoadSideInPassZone
SufficientReturnSpaceInFrontAfterPass
VehicleInFrontDrivingNormally
VehicleInFrontNotAttemptingToPass
NoPersonOnBikeInPassZone
NoVehicleOnRoadsideReadyToComeIntoLane
NoActiveEmergencyVehiclesInFront

SituationInFrontOKtoPass

NoConstructionInPassZone
NoTransitOrSchoolBusStopping
NoPassZone-NotInEffect
LaneMarkingsAllowPass

SituationInBackOKtoPass

NoIntersectionsInPassZone
NoRailroadXInPassZone

OnComingTrafficOKtoPass

ConditionsGoodToPass

PassVehOnTwoLaneRoad

NewPlan	S1 SetPassOnTwoLaneRoadContext() lc_Follow_Lane LookingToPass
S1 ConditionsGoodToPass	S2 AdjustInitPassingParams() lc_ChangeTo_LeftLane MovingIntoPassingLane
S2 ConditionsGoodToPass InPassingLane	S3 AdjustPassingParams() lc_FollowLane PassingVehicle
S3 ClearOfPassedVehicle SufficientReturnSpace	S4 AdjustReturnPassingParams() lc_ChangeTo_RightLane ReturningToOwnLane
S4 ReturnedToLane	S0 Done SetNormalDriveParams() lc_Follow_Lane FinishedPassManeuver
S2 MovingIntoPassingLane NeedToAbortPass	S5 SetFallbackAbortPassParams() AbortingPass
S5 OKtoReturnToLane	S6 AdjustReturnToLaneParams() lc_ChangeTo_RightLane AbortingPass_ReturningToLane
S6 ReturnedToLane	S1 SetNormalDrivingParams() lc_Follow_Lane AbortedPass_LookingToPass
S3 PassingVehicle NeedToAbortPass	S5 SetFallbackAbortPassParams() AbortingPass

World Model Situation

Value Judgment

Behavior Generation

Estimated ~2000 situations

Estimated ~150 FSAs

Driving Task Analysis

6) Define Entities, Events, Attributes, Resolutions, and Tolerances

CrossBuck(pos)
Lights(pos, state)
Crossing Gate(pos)
Signs(pos, facing-dir, text and graphics)
Tracks(pos, dir)
Train(pos, dir)
Lanes(pos, dir, width, curvature)
PassingZone(veh speeds, safety buffer, accel)
eg. All attributes must be recognizable out to 600 to 800 feet

NoConstructionInPassZone
NoTransitOrSchoolBusStopping
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LaneMarkingsAllowPass
NoIntersectionsInPassZone
NoRailroadXInPassZone
NoBridgeInPassZone
NoTunnelInPassZone
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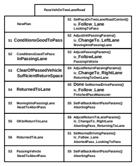
LaneMarkingsAllowPass

SituationInBackOKtoPass

NoIntersectionsInPassZone
NoRailroadXInPassZone

OnComingTrafficOKtoPass

ConditionsGoodToPass



Plan

World Model Entities, Events, and Attributes

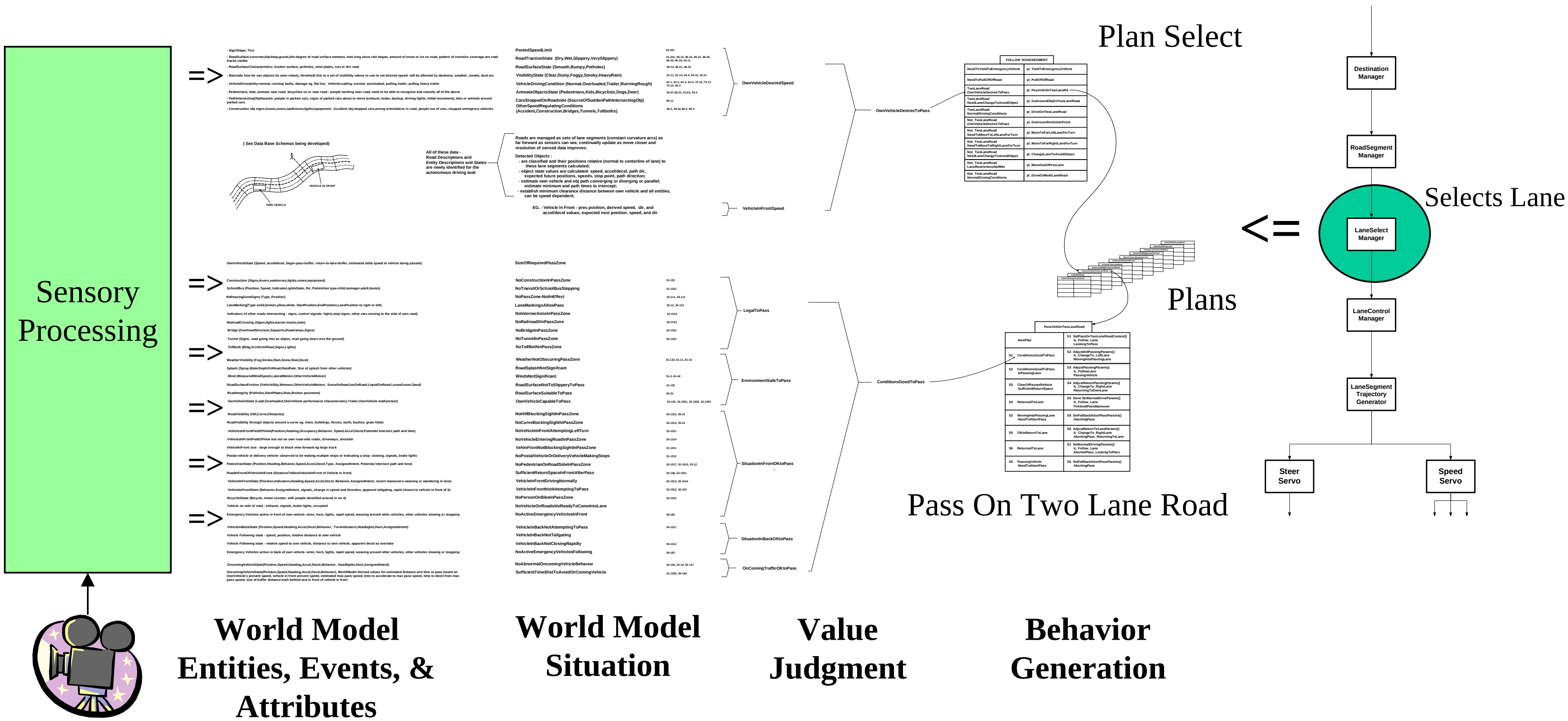
World Model Situation

Value Judgment

Behavior Generation

Driving Task Analysis

7) Define Requirements for Perception



Analysis of knowledge requirements

Knowledge of geometry and dynamics

- **where are things?**
- **where are they going?**
- **what size, shape, feel?**
- **what relationships to other things?**

Knowledge of class membership

- **what are things?**
- **what are their characteristics?**
- **how can they be expected to behave?**

Image processing requirements

A LADAR intensity image of cars in parking lot

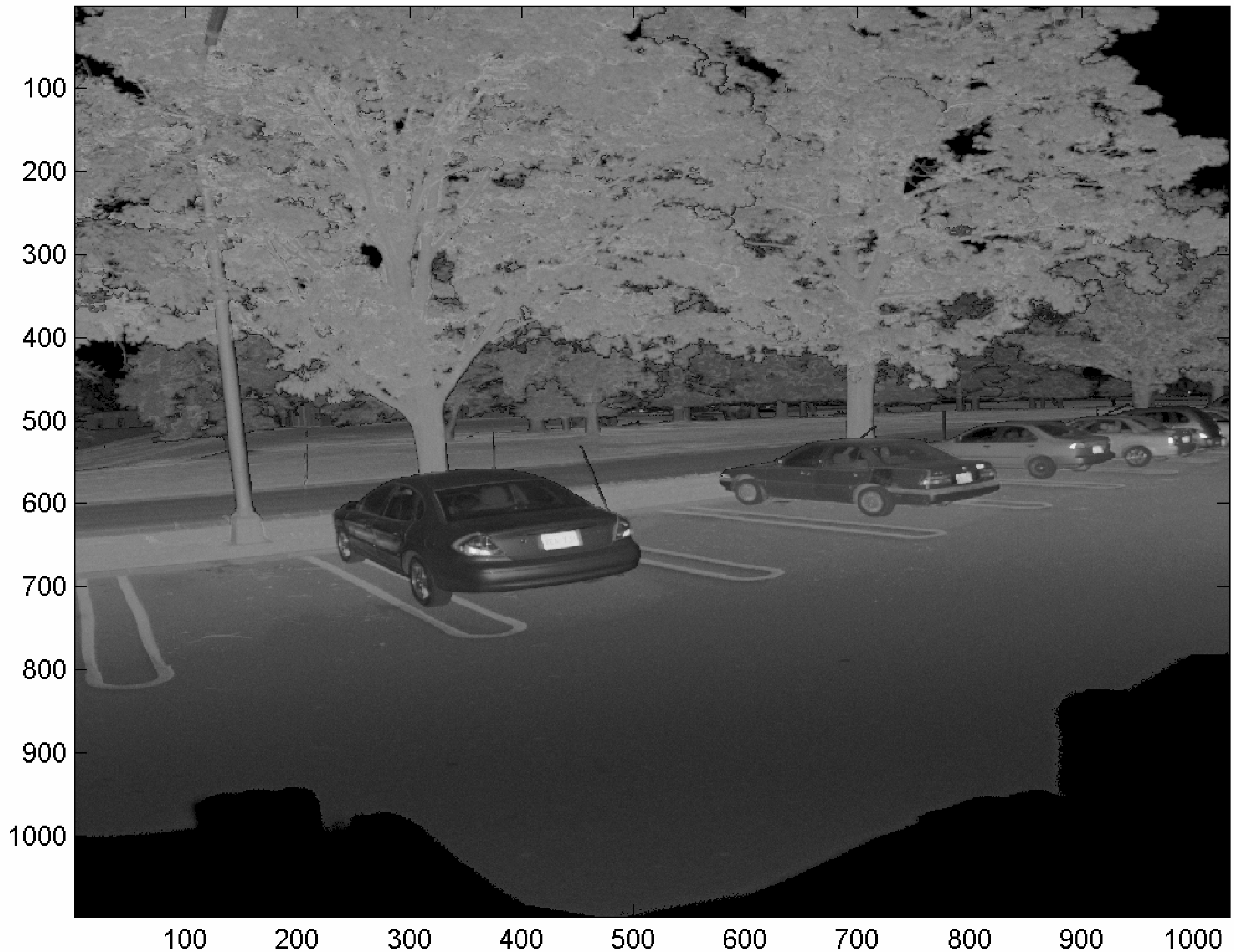


Image processing requirements

Segment object of interest

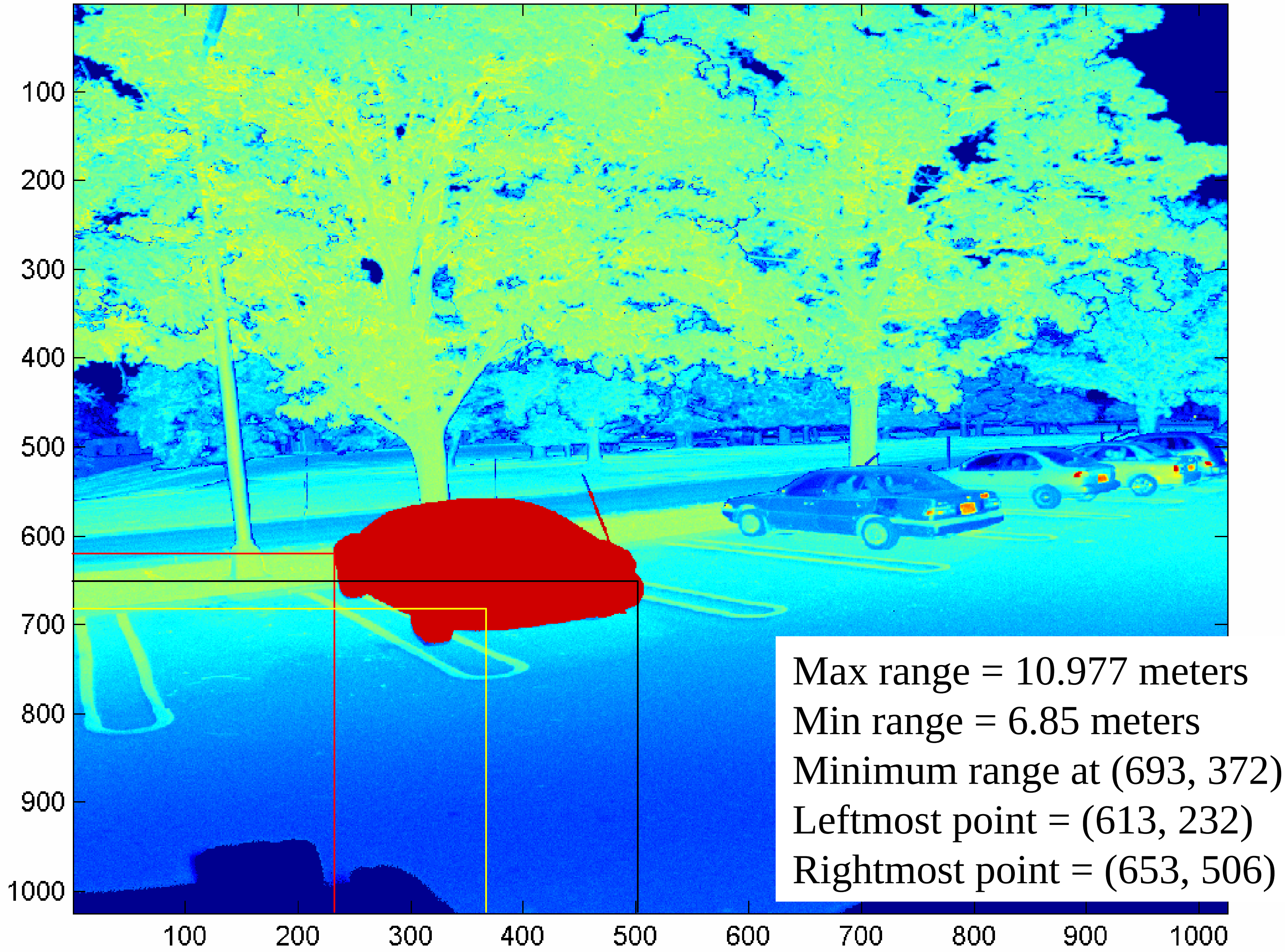


Image processing requirements

Objects on a virtual road

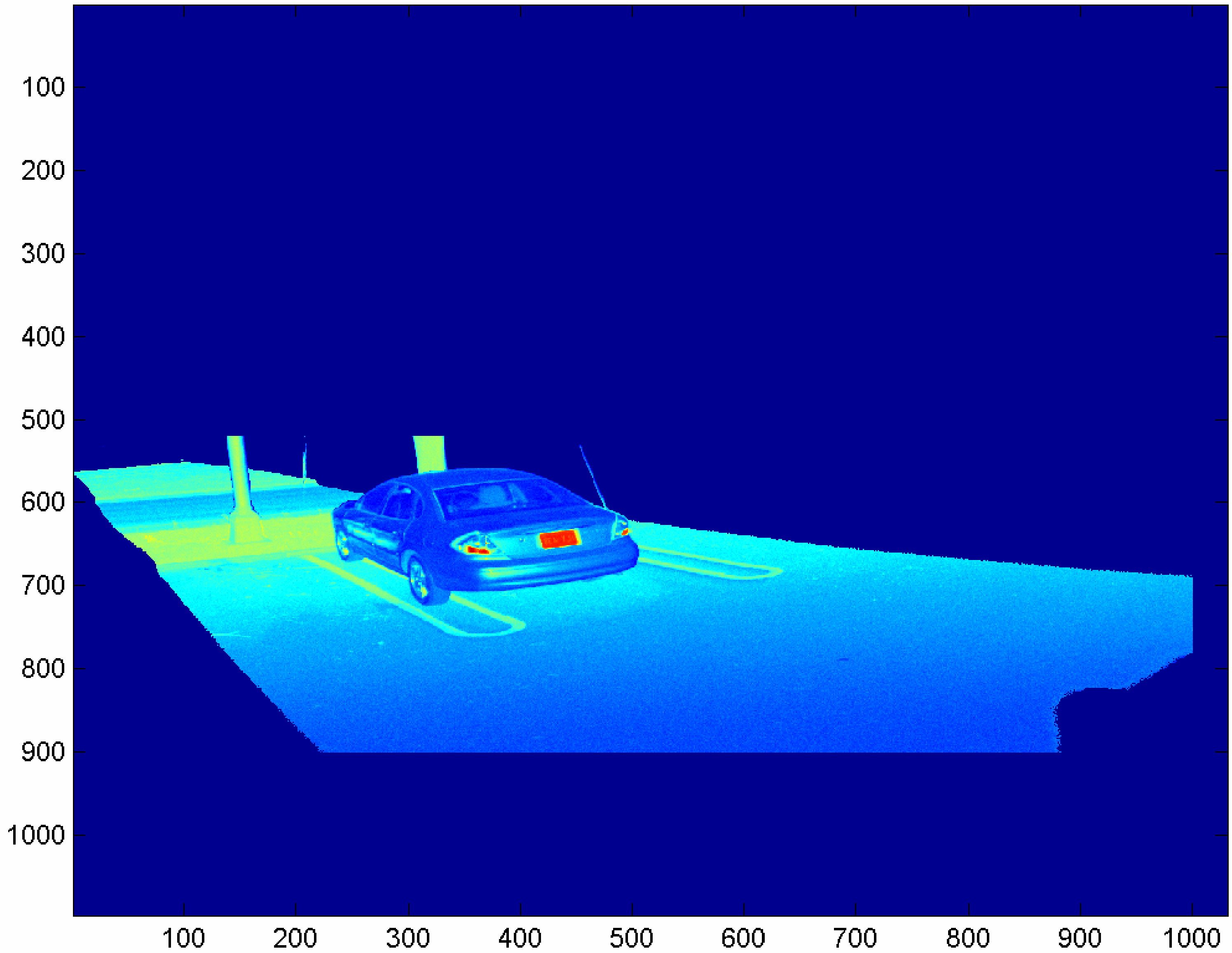


Image processing requirements

Segmented objects on virtual road

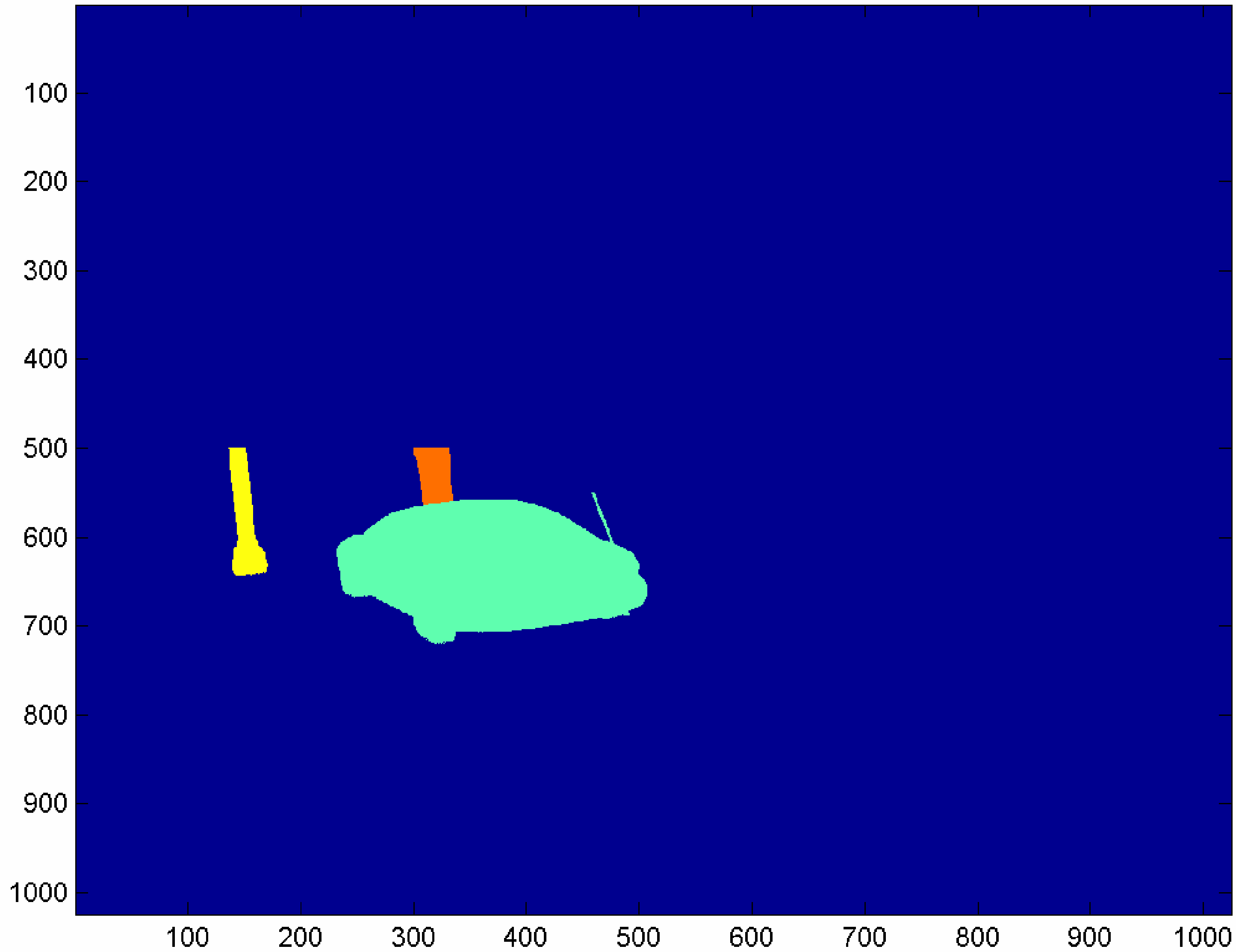
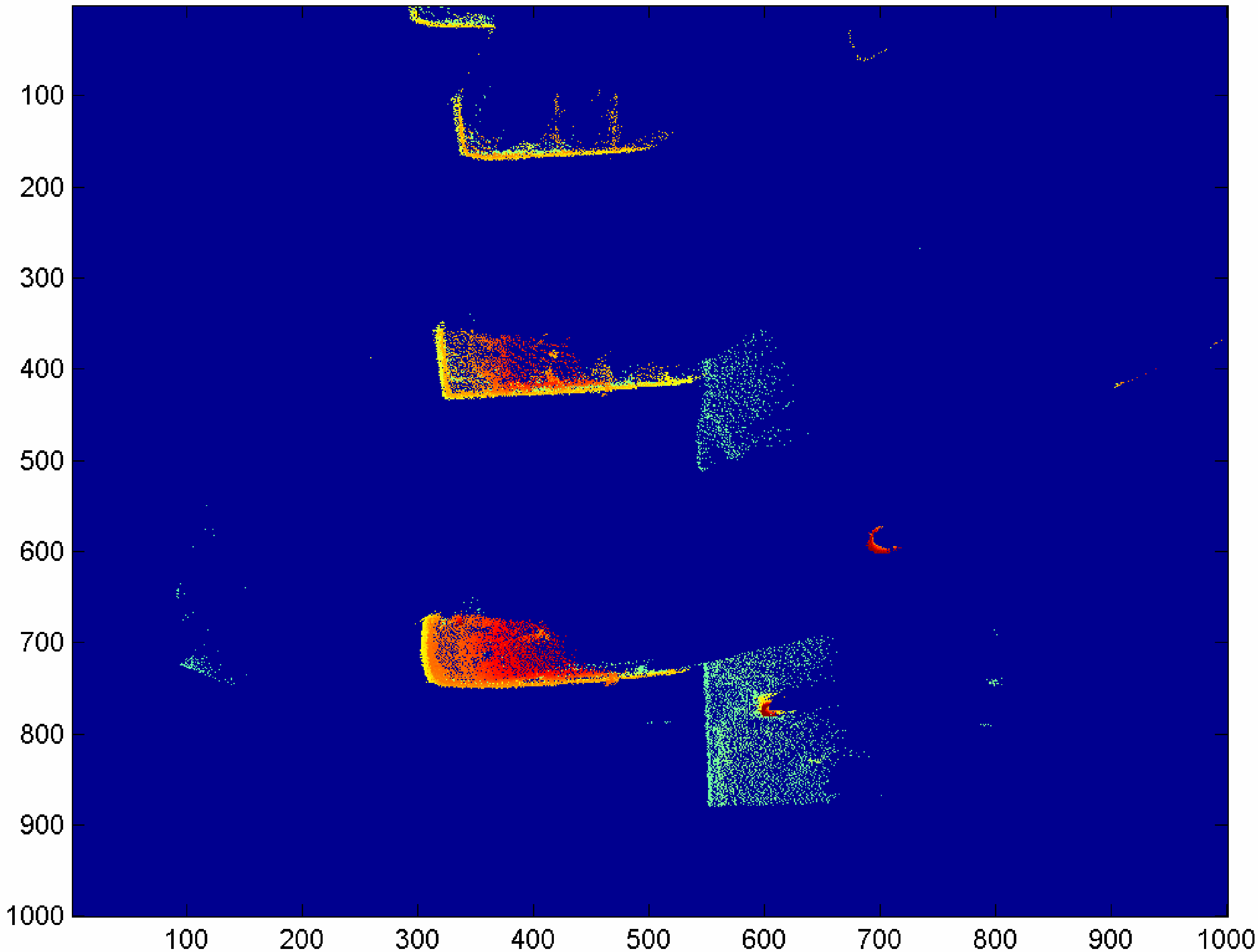
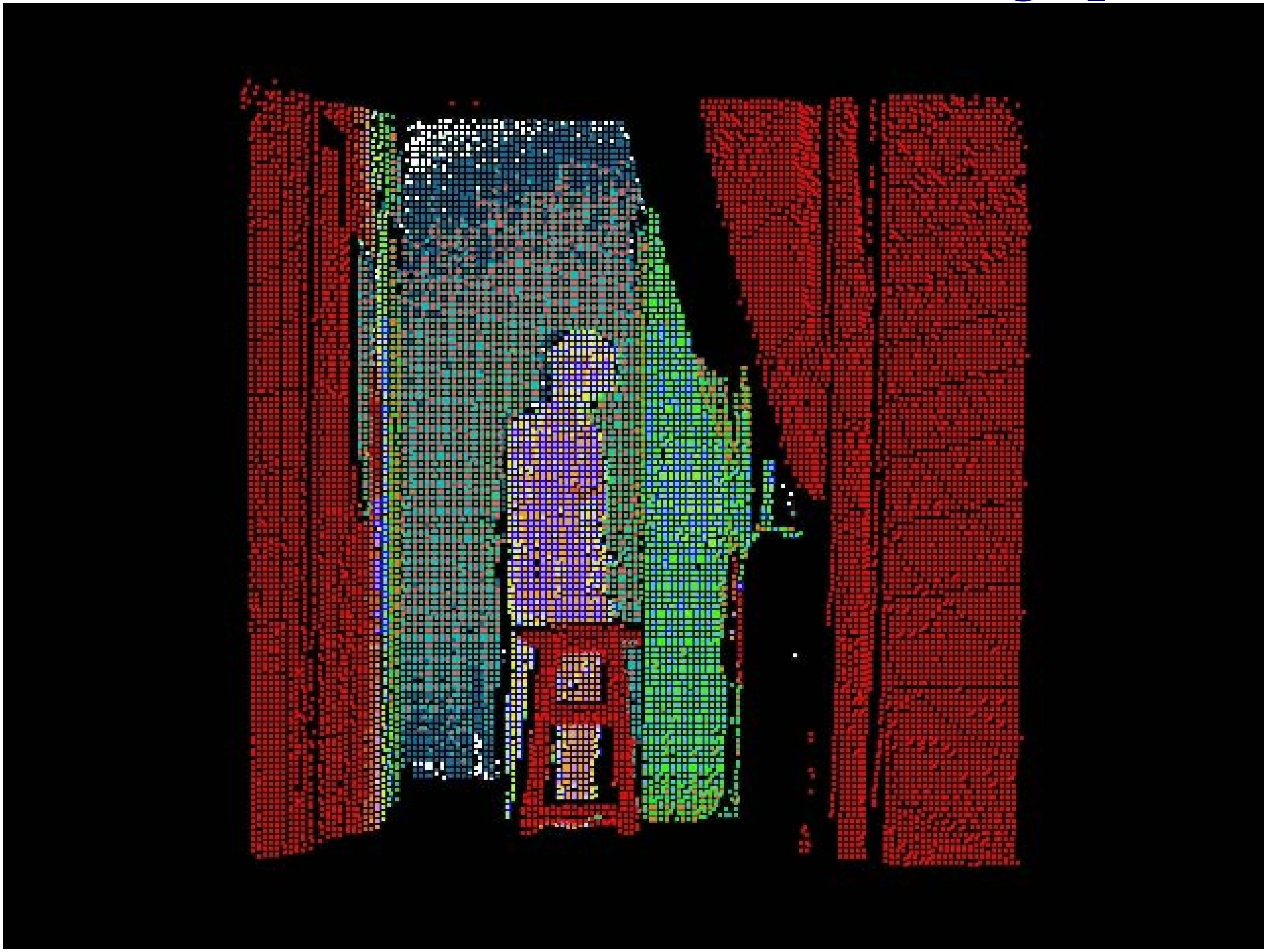


Image processing requirements

Map View of Cars Segmented from Pavement

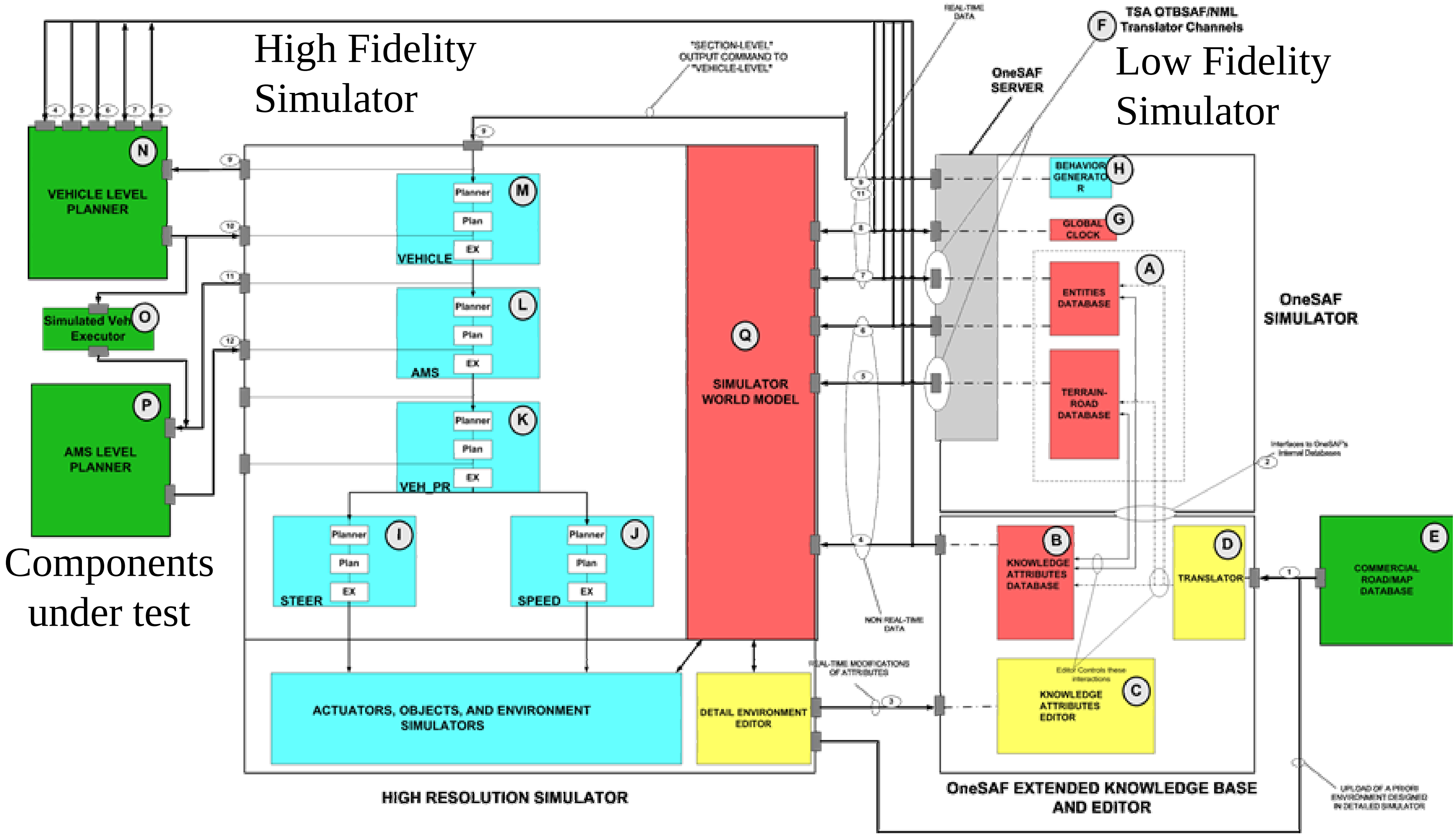


Flash LADAR 128 x 128 range pixels



Flash LADAR   128 x 128 range pixels

Real/Virtual Environment for Software Development



Measures as Specifications

Performance requirements => performance measures

Performance measures => design specifications

Design specifications => technology requirements

Technology requirements => research goals

Example

Performance requirement = pass on two lane road

Performance measures = accelerations, clearance, perception range, accuracy, & latency

Design specs = sensor range, resolution, algorithms for perception & control, computing power

Technology requirements = LADAR specs, camera technology, INS/GPS, computing hardware

Research goals = lasers, detectors, speeds, materials

Example 2

Performance requirement = enter thru hole in ceiling

Performance measures = dimensions, speed, mobility, mapping, target detection, operator workload

Design specs = vehicle performance, sensor specs, perception & control, computing power

Technology requirements = tether control, camera technology, 3-D localization and mapping

Research goals = cable dynamics, kinematics, materials, image registration

Summary and Conclusions

We have begun to move from theory to experiment

Several major experiments have been accomplished

Performance measures are being developed

Performance measures are driving specifications

Specifications are driving technology development